UNIVERSITÄTSKLINIKUM HAMBURG-EPPENDORF

Institut für systemische Neurowissenschaften

Prof. Dr. *med.* Christian Büchel

Bridging Lab and Reality:

A Multi-Level Investigation of Early Adversity, Physiological Processing, and Motivated Behavior in Gamified Virtual Reality

Dissertation

zur Erlangung des Doktorgrades PhD

an der Medizinischen Fakultät der Universität Hamburg

vorgelegt von:

Alexandros Kastrinogiannis

aus Heraklion - Kreta, Griechenland

Hamburg 2025

Angenommen von der
Medizinischen Fakultät der Universität Hamburg am: 05.12.2025

Veröffentlicht mit Genehmigung der
Medizinischen Fakultät der Universität Hamburg.

Prüfungsausschuss, die Vorsitzende: Prof. Dr. Tina Lonsdorf

Prüfungsausschuss, zweite Gutachterin: Prof. Dr. Sarah Hohmann

Zusammenfassung

Belastende Erfahrungen in Kindheit und Erwachsenenalter stellen zentrale Einflussfaktoren für die Entwicklung und Aufrechterhaltung emotionaler Verarbeitung dar. Forschungsergebnisse belegen, dass dysfunktionale Emotionsverarbeitung maßgeblich zur Entstehung von Angststörungen, Depressionen und stressassoziierten Erkrankungen beiträgt. Vor diesem Hintergrund wird im Rahmen dieser Dissertation untersucht, in welcher Weise frühe belastende Erfahrungen (Adverse Childhood Experiences, ACEs) und spätere Stressoren mit Veränderungen affektiver Systeme in Verbindung stehen und wie sich diese in physiologischer Reaktivität, Lernprozessen und motivationalem Verhalten widerspiegeln. Zur Beantwortung dieser Fragestellung wurden psychophysiologische Untersuchungen, eine systematische Literaturübersicht sowie ein neu entwickeltes Virtual-Reality-(VR)-Paradigma eingesetzt.

Studie 1 zeigte, dass frühe Belastungen mit einer reduzierten Differenzierung zwischen neutralen und negativen Reizen assoziiert waren, während spätere Belastungen eine verstärkte sympathische Aktivierung hervorrufen.

Studie 2 fasste den Stand der Forschung zu ACEs und assoziativem Lernen zusammen und identifizierte konsistente Hinweise auf eine eingeschränkte Diskriminationsfähigkeit im Bedrohungs- wie Belohnungslernen, wobei methodische Unterschiede die Vergleichbarkeit einschränken.

Studie 3 nutzte ein gamifiziertes VR-Paradigma zu Annäherungs- und Vermeidungskonflikten und zeigte, dass Teilnehmende mit Belastungserfahrungen Hochrisikokontexte schneller verlassen und Sicherheit häufiger gegenüber Belohnung priorisieren.

Die Befunde verdeutlichen, dass frühe und spätere Belastungen distinkte, zugleich aber komplementäre Veränderungen in affektiven Systemen bewirken. Diese manifestieren sich in veränderter physiologischer Reaktivität, Lernprozessen und Vermeidungsverhalten. Über die spezifischen Befunde hinaus unterstreicht die Dissertation den Wert einer Erweiterung methodischer Horizonte: Der Übergang von kontrollierten Laborexperimenten zu immersiven Paradigmen ermöglicht die Untersuchung von Vermeidungsverhalten in Kontexten, die realitätsnahe Entscheidungsprozesse besser abbilden. Diese Perspektive legt nahe, dass zukünftige Fortschritte nicht nur von einer Verfeinerung theoretischer Unterscheidungen - wie Bedrohung versus Belohnung oder frühe versus spätere Belastung - abhängen, sondern auch von der Nutzung authentischerer Ansätze, die der Komplexität menschlichen emotionalen Verhaltens gerechter werden.

Summary

Adverse experiences in childhood and adulthood represent central influences on the development and maintenance of emotional processing. Research shows that dysfunctional emotion processing substantially contributes to the emergence of anxiety disorders, depression, and stress-related conditions. Against this background, this dissertation examines how early adverse experiences (Adverse Childhood Experiences, ACEs) and later stressors are linked to alterations in affective systems and how these manifest in physiological reactivity, learning processes, and motivated behavior. To address these questions, psychophysiological studies, a systematic literature review, and a newly developed virtual reality (VR) paradigm were employed.

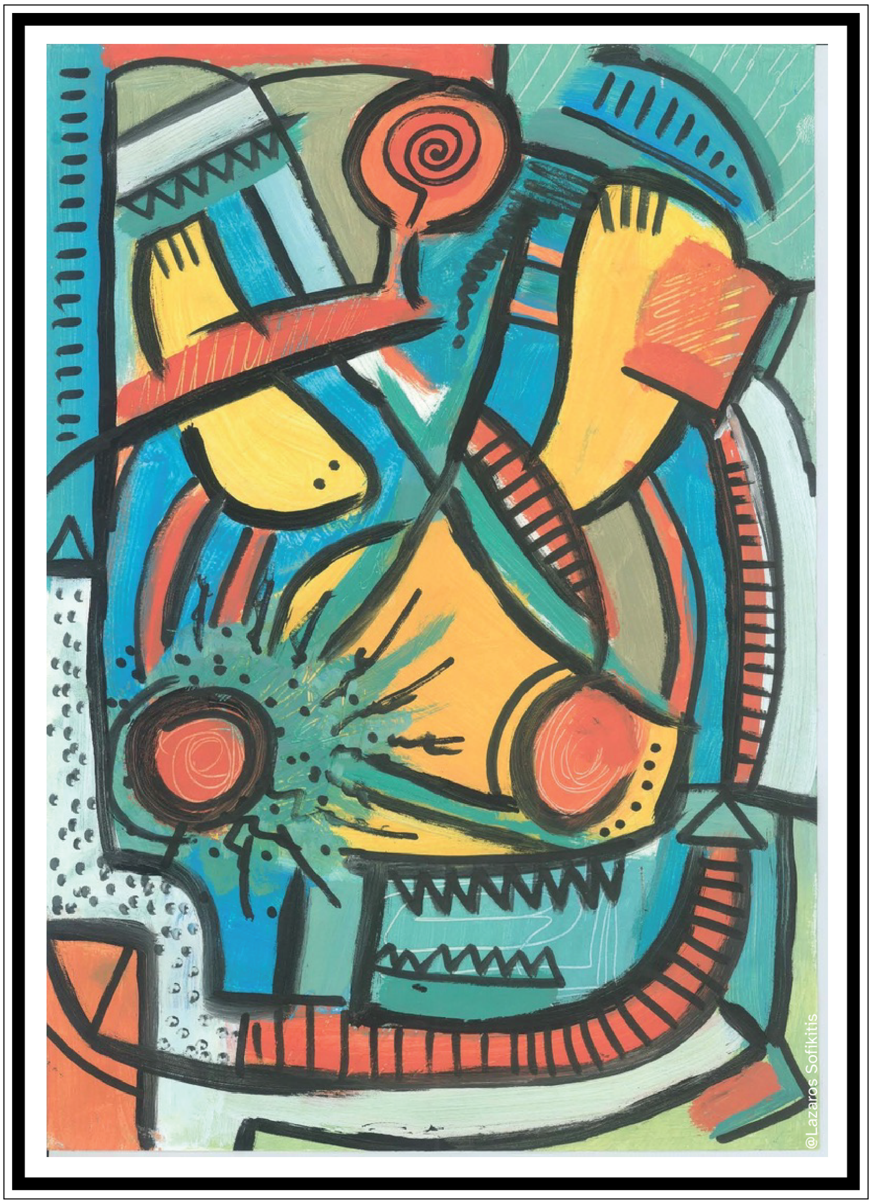
Study 1 demonstrated that early adversity was associated with reduced differentiation between neutral and negative stimuli, whereas later adversity was linked to heightened sympathetic activation.

Study 2 synthesized the literature on ACEs and associative learning, identifying consistent evidence of impaired discrimination in both threat and reward learning, though methodological differences limited comparability.

Study 3 applied a gamified VR paradigm of approach–avoidance conflict and showed that participants with adversity histories exited high-risk contexts more rapidly and more often prioritized safety over reward.

Together, the findings indicate that early and later adversity give rise to distinct yet complementary alterations in affective systems, manifesting in physiological reactivity, learning processes, and avoidance behavior. Beyond the specific findings, the dissertation also underscores the value of broadening methodological horizons: moving from controlled laboratory tasks to immersive paradigms allowed the investigation of avoidance in contexts that better approximate real-life decision-making. This “beyond the lab” perspective suggests that future progress will depend not only on refining theoretical distinctions such as threat versus reward or early versus recent adversity, but also on embracing more authentic approaches that capture the complexity of human emotional behavior.

BRIDGING LAB AND REALITY



A Multi-Level Investigation of Early Adversity, Physiological Processing and Motivated Behavior in Gamified Virtual Reality

ALEXANDROS KASTRINOGIANNIS

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Chapter 1:

GENERAL INTRODUCTION

Chapter 1

GENERAL INTRODUCTION

1.1 The Lasting Impact of Early Adversity on Emotional and Learning Systems

Despite being fundamental to human life, the nature of emotion remains one of the most elusive constructs in psychology and neuroscience. Emotions are fundamental to human experience, influencing our thoughts, behaviors, and interactions on a profound level. Yet, despite their frequent use in both academic discourse and everyday language, there is no universally accepted definition of emotion (Scherer, 2005) and the question of what is an emotion often elicits a wide array of distinct definitions from individuals and scholars alike. However, despite the absence of a universally accepted definition of emotions, there is a general consensus in the scientific community that emotions are multifaceted phenomena involving complex psychological states, subjective experiences, physiological responses and behavioral expressions (Ekman, 1992) and that are fundamental in shaping our actions, perceptions, and feelings (defined as the conscious experience of emotions; Barrett et al., 2018) and consequently influence our interactions with the world and our decision-making processes. Among the basic emotions, fear holds a particularly pivotal role. It is one of the most evolutionarily conserved affective responses, central to survival and rapidly activated in the face of threat (Ekman, 1992; LeDoux, 1996; Panksepp, 1998). Fear is not only a basic and automatic reaction - it is also an adaptive emotion that helps individuals detect and respond to danger. However, when fear becomes dysregulated or chronic, it can give rise to maladaptive outcomes such as anxiety disorders, depression, and post-traumatic stress (American Psychiatric Association, 2013; Damsa et al., 2009; Adolphs, 2013). This makes fear particularly significant in contemporary contexts marked by ongoing global crises - such as wars, pandemics, and environmental instability - where persistent uncertainty and perceived threat can amplify emotional vulnerability on both individual and societal levels (Holmes et al., 2020; Pfefferbaum & North, 2020). Exposure to threat consistently triggers a range of behavioral and physiological responses - such as increased vigilance, defensive actions like avoidance or freezing (Blanchard & Blanchard, 1968; Mobbs et al., 2007), and autonomic changes including heart rate acceleration (Liu et al., 2014), bradycardia (Battaglia et al., 2024) and hormonal shifts (Hermans et al., 2013) - that are shaped by individual differences, context, and the imminence (Abend et al., 2022; Cornwell et al., 2025) or the uncertainty and distance of threat (Grupe & Nitschke, 2013; Topel et al., 2021). While such reactions are fundamentally adaptive by promoting safety and coping, excessive or dysregulated responses are linked to diagnosed anxiety and stress-related disorders (American Psychiatric Association, 2013), as demonstrated across studies of humans and animals in both social and non-social settings (LeDoux, 2012; McEwen, 2007). Crucially, the maladaptive consequences of excessive threat responses often stem not only from the intensity of the physiological reactions themselves but from disruptions in emotional processing systems (i.e., the neural, physiological, and cognitive mechanisms that detect emotionally salient cues, assign them value, and regulate responses). Emotional processing plays a central role in evaluating threat relevance, modulating arousal, and coordinating appropriate behavioral outcomes (Pessoa, 2013). Although frequently studied in the context of threat, emotional processing also underpins how we engage with rewarding stimuli, influencing learning, motivation, and decision-making. It encompasses the psychological mechanisms involved in detecting, responding to, and ultimately integrating emotionally salient experiences, allowing behavior to proceed without ongoing disruption (Rachman, 1980; Gross, 2014, 1998; Ochsner & Gross, 2005). When these mechanisms become compromised (for instance, through a failure to distinguish between threat and safety signals), they can amplify vulnerability to affective disorders (Wauthia & Rossignol, 2016). Thus, in the realm of psychological research, understanding the interface between threat reactivity and emotional processing is essential because they directly affect mental health, behavior, and social interactions, and because dysfunctional emotional processing can lead to severe consequences in daily life (Damasio, 1996; Ekman, 1992; Feldman Barrett & Russell, 1998; Izard, 1992). Importantly, converging evidence suggests that such disruptions in emotional processing are not merely situational, but are often rooted in early adverse experiences that calibrate the developing brain’s affective systems toward heightened threat sensitivity and diminished regulatory capacity (McLaughlin et al., 2015; Teicher & Samson, 2016). Traditionally conceptualized under the umbrella of Adverse Childhood Experiences (ACEs), these include early exposure to abuse, neglect, household dysfunction, and other significant stressors. Exposure to these experiences, especially during sensitive developmental windows, has been shown to alter the trajectory of cognitive, emotional, and physiological development - ultimately shaping how individuals perceive, interpret, and regulate emotional information across the lifespan (Teicher & Samson, 2016). Notably, these developmental changes do not occur uniformly; rather, they give rise to individual differences in how the brain encodes and responds to threat, especially within defensive systems involved in fear and anxiety regulation (Marusak et al., 2018, 2021; McLaughlin et al., 2015; Mickes et al., 2025; Moffitt et al., 2007; Teicher et al., 2016). While regions such as the amygdala are central nodes in neural circuits supporting defensive responses and fear processing, they do not operate in isolation.

They are embedded within wider neural circuits responsible for appraising and modulating the emotional relevance of stimuli more broadly (Toyoda et al., 2011; Bukalo et al., 2015). Expanding on this evidence, neurodevelopmental studies indicate that Adverse Childhood Experiences (ACEs) affect not only circuits specific to fear and anxiety, but also broader networks involved in detecting emotionally salient information and regulating affective responses. Specifically, individuals with a history of ACEs consistently show heightened reactivity in regions such as the amygdala—key to threat detection—alongside atypical amygdala–prefrontal connectivity, including delayed maturation of regulatory circuits following violence exposure (Herringa et al., 2013; Keding et al., 2025; Marusak et al., 2021; Ruge et al., 2024; see Chapter 3). These neural alternations are associated with increased vigilance to threat-related cues, exaggerated physiological arousal, and a tendency to interpret ambiguous stimuli as threatening – features widely recognized as markers of dysregulated emotional processing (Da Silva Ferreira et al., 2014; McCrory et al., 2011; Pollak, 2008). These biased patterns of threat detection and response not only affect momentary reactions but can also shape longer-term behavioral tendencies, particularly in how individuals learn from their environment. This raises an important question: how do these adversity-related shifts in processing threat and reward cues shape long-term patterns of adaptation and learning? A growing body of research suggests that emotional processing systems are deeply entwined with how individuals learn to predict and respond to future outcomes - especially those involving threat and reward (Duffy et al., 2018; McLaughlin et al., 2019). When these systems become biased toward hypervigilance or negative interpretations, they can distort how environmental cues are encoded and associated with consequences - ultimately shaping both threat sensitivity and reward disengagement. This process can be illustrated through the experience of a child raised in an unpredictable household marked by frequent emotional outbursts. Research suggests that in such environments, children often learn to anticipate conflict from subtle cues - like a raised voice or a slammed door - while positive signals such as praise occur inconsistently and carry little predictive value (Pollak, 2008; Dargis & Newman, 2016). Yet, rather than sharpening discrimination, chronic adversity may, over time, blunt responsiveness to both threat and reward signals, leaving individuals less able to flexibly distinguish between safe, dangerous, and rewarding contexts (Ruge et al., 2024; see Chapter 3). Supporting this, physiological research has shown that individuals with early histories of neglect exhibit blunted startle reflexes and diminished postauricular reflex potentiation, indicating compromised responsiveness to both threatening and rewarding stimuli (Quevedo et al., 2015). These dampened reflexive responses may suggest a broader disruption in the body's capacity to flexibly engage with emotionally salient information. Similarly, attenuated neural responses to emotional stimuli - particularly within regions involved in salience detection - have been observed among maltreated youth, suggesting disrupted engagement with emotionally relevant cues (Dargis & Newman, 2016). Such learning biases may be further amplified by the chronic activation of stress pathways often observed in individuals exposed to ACEs, as prolonged stress-hormone activity can alter plasticity in amygdala–prefrontal–hippocampal circuits that underlie threat detection and reinforcement learning (Lupien et al., 2009; Ruge et al., 2024; Tottenham

& Sheridan, 2010). In line with this, experimental studies of fear and reward learning report that adversity-exposed individuals often show blunted physiological differentiation between threat- and reward-related cues, reflecting reduced flexibility in adapting responses to changing motivational contexts (Hanson et al., 2016; McLaughlin et al., 2016; Lis et al., 2020; Ruge et al., 2024; see Chapter 3). While growing evidence supports the association between ACEs and disruptions in emotional processing, important questions remain. In particular, it is unclear how such disruptions manifest across distinct affective domains, such as emotional reactivity and learning. For instance, how do different types or timings of adversity influence variability in physiological responses to emotional stimuli? And to what extent do ACEs alter how individuals form and update associations with threat and reward? Unpacking these mechanisms - and their variability - is central to the empirical work presented in the following chapters. More specifically:

- **Study 1** focuses on physiological reactivity, examining how early and recent adversity are associated with psychophysiological responses to affective stimuli using electromyographic (EMG) and skin conductance response (SCR) measures. This study aims to clarify whether adversity differentially impacts autonomic versus somatic markers of emotion.
- **Study 2** shifts the focus to learning mechanisms, investigating how ACEs impact the formation of threat and reward associations - key processes underlying adaptive behavior and vulnerability to psychopathology. This review synthesizes evidence from fear and reward conditioning paradigms, highlighting both converging patterns and inconsistencies.

1.2 Avoidance in the Aftermath of Threat: Mechanisms and Consequences

Beyond the neural and affective alterations linked to early adversity, one of the most behaviorally salient consequences is the emergence of avoidance as a dominant coping strategy. Behavioral avoidance is characterized by actions taken to avoid situations, environments, or stimuli that are perceived as threatening or anxiety-provoking. While avoidance itself has a survival component in the realm of evolution and is therefore considered adaptive, the excess of avoidance can be counterproductive since it prevents an individual from learning which situations are genuinely dangerous and which are not and is hence considered maladaptive (Barlow, 2002; Craske et al., 2014, 2014; Krypotos, 2015; Lazarus, 1966). The distinction between adaptive and maladaptive avoidance is crucial in clinical psychology, particularly when considering its impact on behavior and recovery. Behavioral avoidance, being more immediately observable, often has direct consequences that can hinder daily functioning. For example, during the COVID-19 pandemic, many people experienced heightened levels of anxiety, uncertainty, and fear (Coelho et al., 2020; Calvano et al., 2021). As a consequence, a person might avoid going to the grocery store out of fear of contracting the virus. While this avoidance may reduce anxiety temporarily, it can lead to long-term issues, such as dependence on others or increased stress. In this example, the avoidance of doing grocery shopping out of fear of the virus reflects passive avoidance (i.e., simply staying away from the perceived threat without taking proactive steps). However, what is therapeutically beneficial is distinguishing this from active avoidance, where the individual still avoids harm but does so by actively engaging with and controlling the threat (LeDoux et al., 2017). For instance, instead of avoiding the grocery store altogether, the person could take precautions like wearing a mask or shopping during off-peak hours. This active engagement, which involves facing feared situations with protective measures, is crucial in therapy as it helps patients confront their fears, learn that the situation is not inherently dangerous, and maintain functionality (J. E. LeDoux & Gorman, 2001). Research in anxiety disorders supports the effectiveness of such approaches, showing that they are essential for reducing long-term avoidance, managing anxiety, and promoting recovery (Holahan & Moos, 1987). This is especially relevant in the aftermath of ACEs, where emotional learning systems may become tuned to anticipate danger, fostering habitual disengagement from potentially threatening stimuli (Kroska et al., 2017; McLaughlin & Lambert, 2017). As such, avoidance represents a behavioral lens through which the long-term impact of ACEs can be observed - not just in clinical symptomatology, but in everyday decision-making and social functioning. This pattern of disengagement can be situated within broader models of emotional processing, which encompass perception, expression, and regulation of affect. As illustrated in Figure 1, avoidance emerges as a regulatory strategy that - unlike adaptive responses such as reappraisal or problem solving - often reflects maladaptive coping when overused, particularly in the wake of chronic threat (Folkman & Lazarus, 1980; Gratz & Roemer, 2003; Gross, 1998).

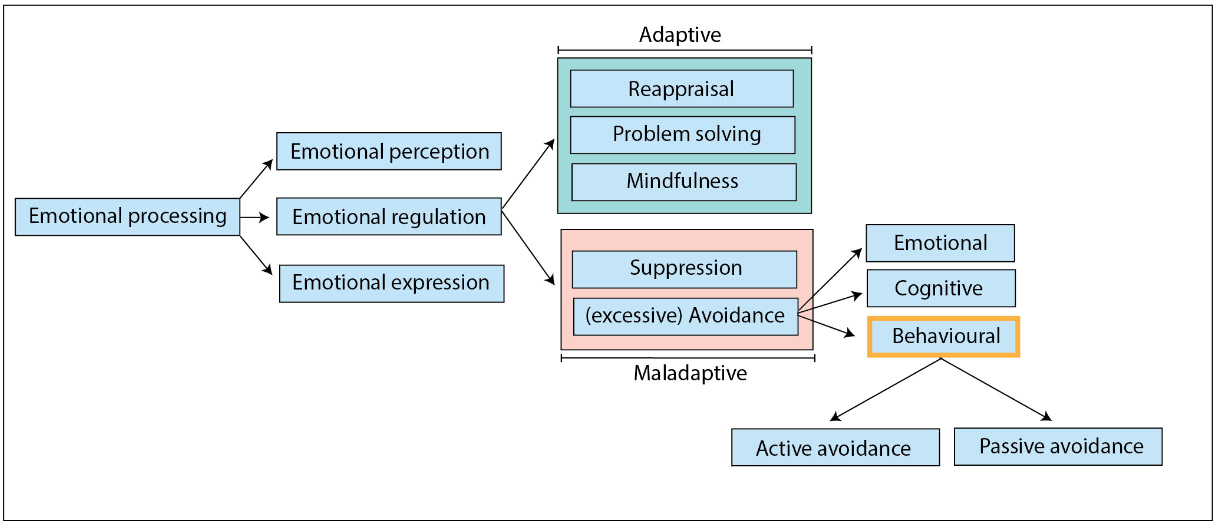
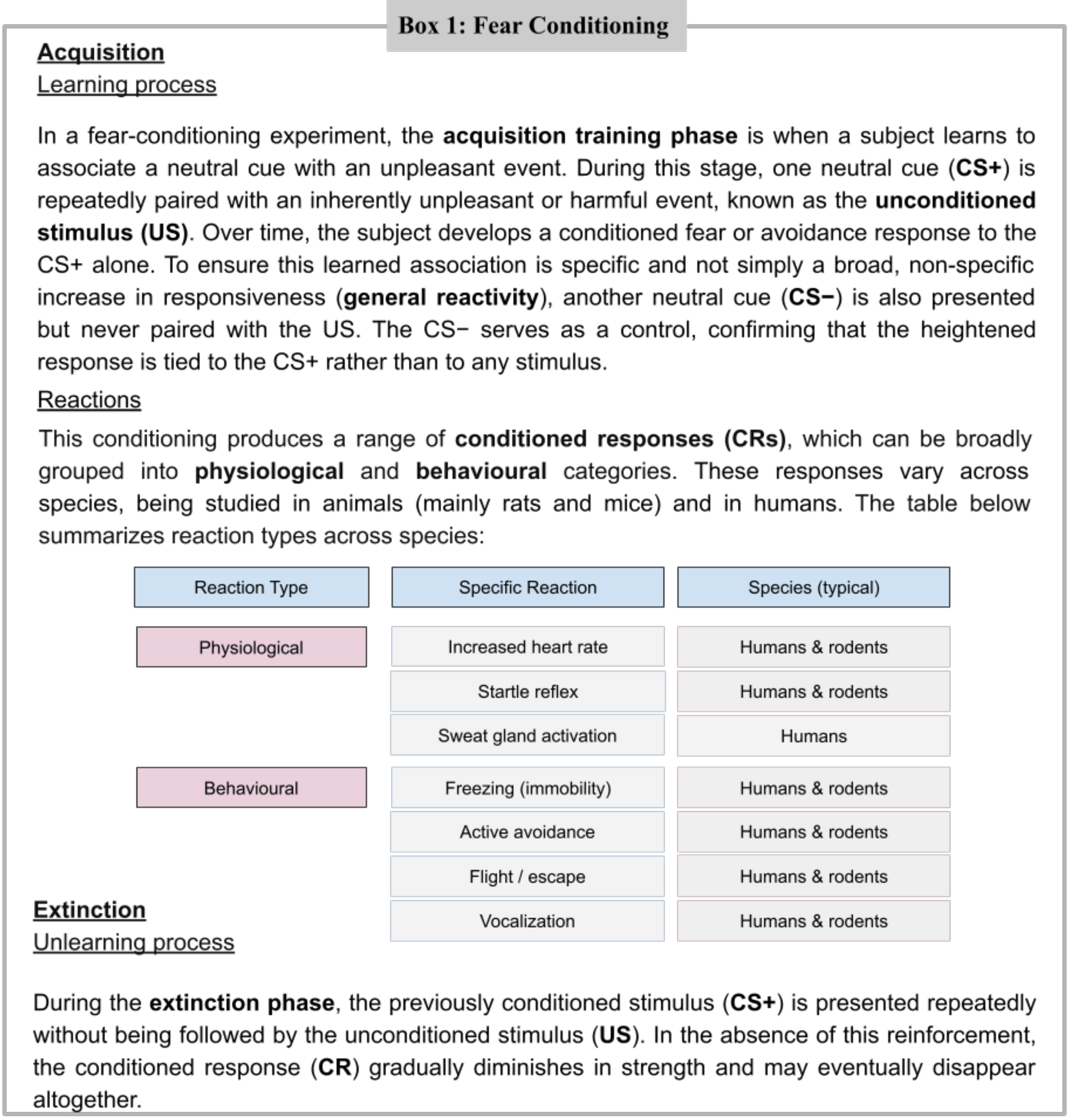


Figure 1: Schematic representation of emotional processing and regulation strategies. Emotional processing encompasses perception, regulation, and expression of affect. Regulation strategies can be adaptive - such as reappraisal, problem solving, and mindfulness - or maladaptive, including suppression and excessive avoidance. Avoidance may manifest across emotional, cognitive, and behavioural domains, with behavioural avoidance further divided into active (threat approached with protective actions) and passive (threat avoided without engagement) forms.

The study of avoidance is fundamentally grounded in the principles of classical conditioning, particularly fear conditioning (see Box 1) which illustrates how organisms learn to anticipate and respond to fear-related cues. A foundational example can be traced back to the famous "Little Albert" experiment in 1920 (Watson & Rayner, 1920), which demonstrated that fear responses could be conditioned by pairing a neutral stimulus (a white rat) with an aversive event (loud noise). While not directly focused on avoidance, it laid the groundwork for understanding how fear and avoidance behaviors can be conditioned. Building on this, the two-factor theory (Mowrer, 1947, 1951, 1956), proposed that fear is first acquired through conditioning (i.e. a neutral stimulus becomes a conditioned stimulus that elicits a fear response), and avoidance behaviors are then reinforced through the reduction of fear, which serves as a negative reinforcer. In this framework, for example, Little Albert might engage in avoidance to prevent contact with the conditioned stimulus (the white rat), thereby reducing his fear response.



Box 1: Fear Conditioning

Acquisition

Learning process

In a fear-conditioning experiment, the **acquisition training phase** is when a subject learns to associate a neutral cue with an unpleasant event. During this stage, one neutral cue (**CS+**) is repeatedly paired with an inherently unpleasant or harmful event, known as the **unconditioned stimulus (US)**. Over time, the subject develops a conditioned fear or avoidance response to the CS+ alone. To ensure this learned association is specific and not simply a broad, non-specific increase in responsiveness (**general reactivity**), another neutral cue (**CS−**) is also presented but never paired with the US. The CS− serves as a control, confirming that the heightened response is tied to the CS+ rather than to any stimulus.

Reactions

This conditioning produces a range of **conditioned responses (CRs)**, which can be broadly grouped into **physiological** and **behavioural** categories. These responses vary across species, being studied in animals (mainly rats and mice) and in humans. The table below summarizes reaction types across species:

Reaction Type	Specific Reaction	Species (typical)
Physiological	Increased heart rate	Humans & rodents
	Startle reflex	Humans & rodents
	Sweat gland activation	Humans
Behavioural	Freezing (immobility)	Humans & rodents
	Active avoidance	Humans & rodents
	Flight / escape	Humans & rodents
	Vocalization	Humans & rodents

Extinction

Unlearning process

During the **extinction phase**, the previously conditioned stimulus (**CS+**) is presented repeatedly without being followed by the unconditioned stimulus (**US**). In the absence of this reinforcement, the conditioned response (**CR**) gradually diminishes in strength and may eventually disappear altogether.

Box 1. Physiological reactions include freezing (complete cessation of movement; passive coping), increased heart rate (tachycardia, measured via ECG), startle reflex (rapid, involuntary motor response; in humans often measured as eyeblink EMG), and sweat gland activation in humans (commonly quantified via SCR). Behavioural reactions include active avoidance (moving away from the conditioned stimulus to prevent exposure to the unconditioned stimulus), flight or escape behaviours (rapid withdrawal from threat), and vocalizations (audible in humans/primates, ultrasonic in rodents). Animal data are primarily derived from rodent models, especially rats (Rattus norvegicus) and mice (Mus musculus).

During the mid-20th century, more sophisticated avoidance learning paradigms emerged in both animal and human research (Ader & Tatum, 1961, 1963; Baer, 1960; Weiner, 1969). These paradigms involve an explicit action by the subject to avoid an aversive stimulus - for example, lever pressing in rodents and pressing a bar or response button in humans. This research established that, once fear is conditioned, individuals may develop avoidance behaviors as they seek to prevent exposure to the conditioned fear stimulus. An important development in avoidance research was

Bolles' proposal that animals are equipped with innate tendencies aimed at protecting them from predation, known as species-specific defense reactions (SSDR; Bolles, 1970). The significance of this theory lies in its challenge to the prior understanding that avoidance was solely based on learned associations between an organism's response and the avoidance of a harmful stimulus. Bolles argued that purely operant models of avoidance learning ignored innate components, such as instinctive reactions to threats, that are essential for explaining avoidance behaviors. According to the theory, if the operant response required to avoid an aversive stimulus aligns with an organism's innate defensive behaviors -those naturally linked to survival threats- the acquisition of avoidance learning will be faster. This is because such responses are more easily triggered by aversive stimuli. In contrast, responses to less evolutionarily primed events require more complex neural processing to activate the relevant mechanisms and are less readily influenced by aversive stimuli (Öhman & Mineka, 2001; Phelps, 2011). Building on the idea that responses to threats might be more complex than simple conditioned associations, subsequent research expanded the understanding of avoidance. Rather than viewing avoidance as a simple, conditioned, automatic response, it came to be seen as a complex interaction involving emotional and cognitive processes, such as fear anticipation, expectations of danger, and the mental processing of threats (Seligman & Johnston, 1973). This shift moved the field towards a cognitive-emotional perspective and highlighted the importance of internal mental states in avoidance behavior (Bouton, 2007).

- **Study 3** is inspired by decades of research on avoidance - from early fear-conditioning paradigms to models incorporating innate defense responses and cognitive–emotional processes - and applies these perspectives to examine approach–avoidance conflict under threat in a setting that more closely approximates real-life decision making. Leveraging an ecologically valid, gamified paradigm that enhances immersion and authenticity (see Chapter 1.3), the study moves beyond traditional laboratory constraints to capture how individuals balance risk avoidance and reward pursuit, identifying behavioral and physiological markers that differentiate adaptive from maladaptive patterns.

1.3 Beyond the Lab: Expanding Experimental Boundaries

In Plato's "Allegory of the Cave," where Plato describes a group of people who have been chained inside a dark cave for their entire lives, facing a blank wall. Behind them, a fire burns, and objects move between the fire and the prisoners, casting shadows on the wall they face. The prisoners, knowing nothing beyond these shadows, assign names and meaning to them, believing the shadows to be the entirety of existence. Yet, these shadows are merely illusions—distorted versions of the true objects that exist beyond their limited view. The cave and shadows represent the constraints of perception and the superficial understanding we can gain from our senses alone, whereas the reality outside the cave, illuminated by the sun, symbolizes the deeper knowledge and truth that can be understood through reason and deeper inquiry (Plato, 1943). Similarly, in cognitive neuroscience including the studying of emotional processing, much of the progress has been achieved through controlled laboratory settings, which, like the cave, offer a controlled but limited perspective on emotional experiences. These settings, while useful for isolating specific neural mechanisms by regulating sensory stimuli, motor responses, and other task variables, provide only a simplified and narrow view of the complex reality of the human mind including emotions. Just as the shadows in the cave do not fully capture the essence of the true forms outside, laboratory conditions do not fully represent the rich and multifaceted nature of emotions as they occur in real-world contexts. To gain a more comprehensive understanding of emotional processing, it is essential to move beyond these controlled environments and explore more naturalistic settings that reflect the full spectrum of human experience. Just as knowledge in Plato's allegory required leaving the cave and confronting reality outside, progress in affective neuroscience may require stepping beyond controlled laboratory paradigms into more immersive and naturalistic approaches. This chapter will address the essential components for advancing psychological research toward experiments that more closely reflect real-life emotional experiences. It will begin by discussing how realistic and engaging environments can enhance the study of emotions, followed by the assumption that balance between experimental control and naturalism ensures the accuracy of measuring emotional responses (Section 1.3.1). Finally, the chapter will explore approaches, such as gamification, which can boost participant engagement and generate richer data (Section 1.3.2).

1.3.1 Immersion, Authenticity and Ecological Validity: The Role of Naturalism in Research

Immersion and Authenticity

Assuming that advancing laboratory research in cognitive and emotional neuroscience requires creating scenarios that mirror everyday life, one might argue that the objective is to make these settings “more naturalistic.” The first step in achieving naturalism is to understand what makes a context or scenario genuinely feel natural to an individual. Is it the accurate representation of objects and the self within the environment? Or is it the perceptual fidelity of the experience, such as the difference between 2D and 3D visual representations? When discussing the benefits of naturalism in research, it is important to clarify that this does not imply a perfect simulation of reality as one would perceive it in everyday life. Rather, the goal is to create environments that more closely resemble key aspects of real-world scenarios in order to elicit the emotions and responses of interest more effectively. A more appropriate term to describe this approach might be authenticity (from the Greek authentikós, meaning “original” or “genuine”), referring to the creation of experimental settings that, while not identical to real life, provide an experience that is believable and relatable enough to evoke natural emotional and cognitive responses from participants. Beyond visual cues, we must also consider other sensory elements that shape our perception of reality (Berthoz, 1994; Driver & Spence, 2000), such as sound (Stanton & Spence, 2020), which contributes to the ambiance of a setting; tactile sensations, which provide a subjective sense of physical presence; and even olfactory cues, which can evoke memories and emotions (Herz, 2016). These elements, among others, play a role in what we call the state of immersion. The conceptual debate around what constitutes immersion and whether it necessitates a faithful replication of reality - an inherently complex and multifaceted concept - extends beyond the scope of this thesis. Therefore, for the purposes of this work, immersion will be defined as follows:

> ***Immersion*** is the degree to which an individual feels present and fully engaged in an environment or experience, often leading to a diminished awareness of the real world surroundings. It involves a blend of sensory engagement, emotional involvement, and cognitive integration, where perceptual and cognitive processes are engaged with the mediated environment to create a compelling illusion of reality (Witmer and Singer, 1998).

The goal of creating natural (or authentic) settings in experimental research is not a new concept. In animal studies, researchers have long sought to implement more authentic experimental conditions by utilizing open environments. For example, studies involving spatial navigation have employed free-moving rats and primates to better understand their natural behaviors (Ainsworth et al., 1969; Wall et al., 1967; O’Keefe & Dostrovsky, 1971; Taube, 1998). More recently, this approach has been further developed in macaque research, facilitated by technological advancements that allow for more sophisticated operationalization of these naturalistic studies in the field of empirical neuroscience (Berger et al., 2020; Mao et al., 2021; Testard et al., 2024; Voloh et al., 2023). At the human level, creating authentic experimental contexts has been operationalized in various ways, such as through free-walking and open-field studies (Walz et al., 2016). Additionally, wearable technology has been used to capture real-life events, which later serve as stimuli during autobiographical memory recall or for gathering spatial data (Chow & Rissman, 2017; Dassing et al., 2020; Nicolás et al., 2021).

Balancing Control and Realism in Experiments

However, this approach presents significant challenges, including high costs in terms of both time and financial resources (Matusz et al., 2019), and a considerable loss of experimental control (see Chapter 1.3.2). The challenge of balancing the creation of authentic experimental contexts while retaining key controlled elements can be addressed through the use of tools like VR and Mixed Reality (MR). Although these technologies are not new (Barnard, n.d.), VR has been used in psychological research since the 1990s (Maples-Keller et al., 2017), their rapid adoption in modern research has been facilitated by the growing commercial availability (Zoting, n.d.) and affordability of VR headsets , making them more accessible for contemporary laboratories and training environments (Leite & Vieira, 2025). To this end, while immersion and authenticity are distinct concepts, their interplay may influence the effectiveness of experimental settings. A higher degree of immersion may enhance the perceived authenticity of an environment, potentially leading to more genuine emotional and cognitive responses. Conversely, even in less immersive settings, a high level of authenticity can still evoke natural reactions and provide valuable data. For example, in a virtual reality experiment, a fully immersive 3D simulation of a crowded street may feel more authentic to participants and elicit stronger approach-avoidance responses. However, even in a less immersive 2D video scenario with a similar theme, the authenticity of the narrative or visuals could still evoke meaningful reactions. Although the relationship between immersion and authenticity is not strictly linear, their interaction can contribute to creating environments that more accurately elicit the emotions and behaviors of interest, offering a valuable approach for research in cognitive and emotional neuroscience (Figure 2). Although this specific interplay between immersion and authenticity is not directly investigated in the present thesis, it represents an important conceptual backdrop for interpreting how different experimental settings may shape emotional and behavioral responses.

Ecological Validity: Erosion of Meaning or Gradual Evolution?

Introduced in the 1940's by psychologist E.Brunswik, ecological validity was used in the context of his lens model (together with terms "representative design" and "intra-ecological correlation"), where he emphasized the importance of designing experiments that mirror the complexity of natural

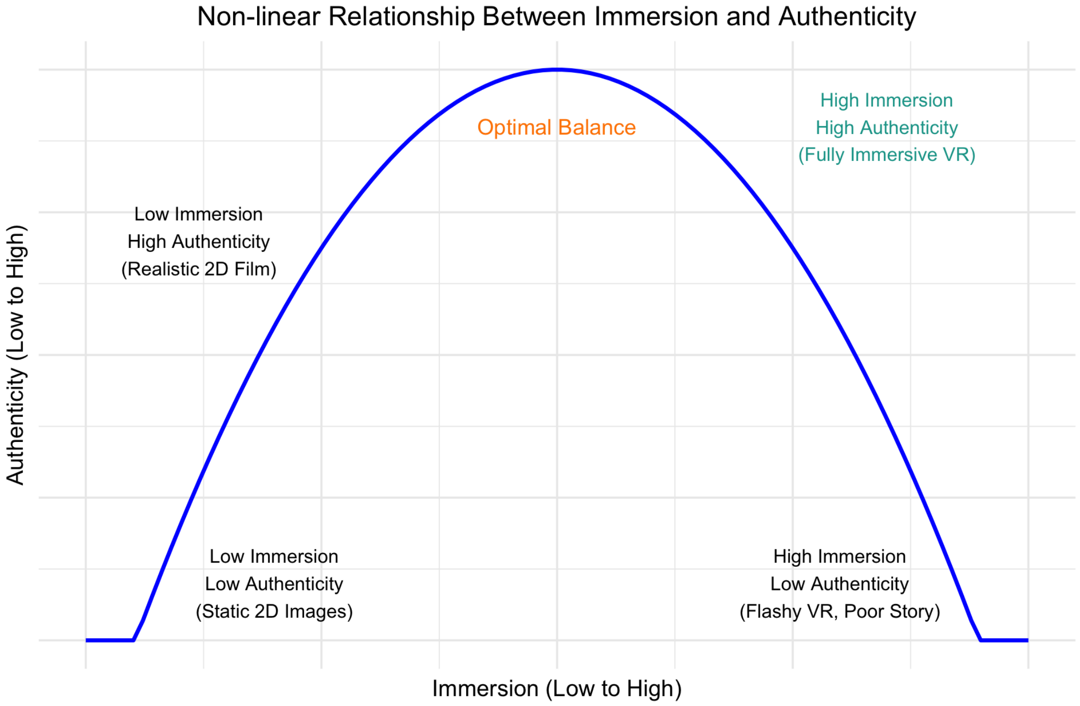


Figure 2: The graph illustrates the non-linear relationship between immersion and authenticity, highlighting how different combinations of these factors influence emotional and cognitive engagement. Various scenarios, ranging from low immersion/low authenticity (e.g., static 2D images) to high immersion/high authenticity (e.g., fully immersive VR with a representative narrative), demonstrate how both factors interact to evoke naturalistic responses.

environments to better understand how organisms interact with the world around them. Brunswik's idea of representative design suggests that experiments should account for the variability and correlations present in real-life situations to enhance their ecological validity. The term is one of the most frequently encountered in VR research, especially when highlighting the advantages of VR methods in simulating real-world environments. A significant debate surrounds the term ecological validity, particularly regarding whether it continues to serve its original purpose. Its widespread use has led to concerns about misinterpretation, especially in relation to its conflation with the concept of representative design. This confusion has been described as a situation where ecological validity is "in danger of losing its meaning as its use increases," reflecting concerns that the term, originally a Brunswikian concept, is becoming diluted through overuse (Hammond, 1998). The core of the issue lies in the following divergence of definitions and interpretations:

A) The ability to generalize findings (original meaning):

The original use of ecological validity, according to Brunswik, is about the generalizability of the results - how well the findings from an experiment can be applied to real-world situations. The focus here is not just on whether the experiment resembles real life but on whether the behaviors and outcomes observed in the lab will hold true in everyday settings, regardless of how closely the experimental setup mimics reality.

B) Resemblance to Real-World Situations (deviation from the original term):

This use of the term emphasizes how well an experimental setup mimics or looks like real-life conditions. In this view, if the environment of the experiment feels realistic or resembles everyday life, it is considered to have high ecological validity. This interpretation prioritizes surface-level realism in the experimental design.
In this work, ecological validity will be considered according to its original definition (i.e. the ability to generalize findings).

1.3.2 Engaging Methods: The Power of Gamification in Experimental Design

The Challenge of Motivation in Human Experiments

Motivation plays a crucial role in both human and animal behavior, particularly in experimental studies where maintaining engagement is essential to obtaining meaningful data (Deci & Ryan, 2000; Ryan & Deci, 2000). In animal research, natural survival instincts, such as foraging for food, provide a powerful motivational drive. However, achieving this level of intrinsic motivation in human participants poses a unique challenge. In animal experiments, animals exhibit strong goal-directed behavior because their motivation is inherently tied to basic biological needs like hunger. For example, in maze experiments, rodents are highly motivated to find food rewards, and this drive ensures that their behavior is focused and persistent. This form of intrinsic motivation, directly linked to survival, creates an environment where the animal is fully engaged, and their actions are consistently aligned with the goals of the experiment. This has been widely used in operant conditioning studies, where animals are trained to perform tasks in exchange for food, showing predictable and reliable patterns of behavior based on motivation (Skinner, 1954). In contrast, human participants rarely face such immediate biological pressures during experiments. Their motivation tends to rely on extrinsic factors like monetary incentives, task interest, or social validation (Ryan & Deci, 2000), which may not evoke the same intensity or persistence of effort. As a result, human behavior in experimental tasks is more susceptible to fluctuations in engagement due to boredom, fatigue, or distraction, potentially undermining task focus and goal-directed behavior (Boksem et al., 2005; Fortenbaugh et al., 2017). This gap in motivational intensity is particularly relevant for experimental tasks - such as the one explored in the third study of this thesis - that aim to capture goal-directed behavior under varying conditions. To address this, we incorporated elements designed to enhance engagement, laying the groundwork for the gamification approach described next.

What is gamification?

The precise origin of the term “gamification” is difficult to pinpoint, as there was no formal introduction or individual who claimed its creation. It is believed to have emerged in the early 2000s

(Marczewski, 2013; Sailer et al., 2017), possibly originating from the media sector. However, there are different claims about its beginnings, with mentions in several articles, blogs, forums, and online discussions (Deterding et al., 2011; Paharia, 2010). Notably, the term experienced rapid growth in usage, with its peak popularity occurring within the first four years after being introduced in academic literature (Trinidad et al., 2021). At its core:

Gamification refers to the **application of video game design** principles -such as engagement and motivation- **to non-game contexts**, enhancing user experience and participation (Deterding et al., 2011) and relies on four semantic components: *game*, *elements*, *design* and *non-game contexts*.

This definition will be used within this work to refer to gamification. It draws on principles from game design to transform typically mundane tasks into more engaging and enjoyable experiences. By incorporating these elements, gamification taps into **intrinsic** both intrinsic and **extrinsic** motivational systems, which are essential in fostering greater involvement and persistence in research tasks. *Intrinsic* motivation is driven by internal rewards, such as the satisfaction and enjoyment derived from completing a task. Game elements like challenges, achievement badges, and progress tracking can appeal to this type of motivation by providing a sense of accomplishment, mastery, and competence. These game-like mechanisms provide participants with an intrinsic sense of progress and achievement, encouraging continued engagement with the task, however, always dependent on the context in which the gamification is being implemented, as well as on the users using it (Hamari et al., 2014). On the other hand, *extrinsic* motivation relies on external rewards, such as tangible incentives (e.g., prizes or points) or social recognition (e.g., leaderboards). Gamified elements like points systems, levels, and reward-based incentives cater to extrinsic motivation by offering immediate, visible feedback and rewards for performance. By appealing to participants' desire for external validation or tangible rewards, gamification can drive sustained attention and effort during experimental tasks. In the present work, gamification elements - such as token collection (apples) and scoreboards - were incorporated into the virtual task (see Study 3) to stimulate both intrinsic motivation (through challenge and mastery) and extrinsic motivation (via visible rewards and performance feedback), thereby enhancing participant engagement in an otherwise abstract behavioral paradigm.

The Impact of Autonomy: Unlocking Motivation Through Choice and Freedom

This connects directly to Self-Determination Theory (SDT), which explains how game design elements influence motivation by addressing core psychological needs such as autonomy, competence, and relatedness (Deci & Ryan, 1985; Deci & Vansteenkiste, 2004). For example, by giving participants control over their progress through points or levels, experiments cater to the need for **autonomy**, a key pillar of SDT. For the purpose of this work, autonomy is of most interest. *Autonomy* encompasses two key aspects: the freedom to make decisions based on one's own values and interests (Deci & Ryan, 2012) and the sense of volition, where individuals act without feeling external pressure or enforcement (Vansteenkiste et al., 2010). This means that autonomy provides participants not only with decision freedom, allowing them to choose between different actions, but also with task meaningfulness, giving them a sense of purpose and ownership over the task at hand (Sailer et al., 2017). In contrast to conventional laboratory experiments (see section 1.3.1), where maintaining control over an experimental setting is crucial for behavioral research, introducing autonomy might reduce this level of controllability. However, autonomy plays a significant role in enhancing motivation, as it allows participants to feel a sense of psychological freedom and volition in fulfilling a task (Van den Broeck et al., 2010; Vansteenkiste et al., 2010).

- **Study 3** applies immersive virtual reality and gamification principles to create an experimental setting that enhances authenticity and participant engagement. By integrating meaningful choices and progress indicators, the design fosters autonomy and positions participants as active agents rather than passive subjects. This combination of **immersion**, **autonomy**, and **game design elements** is intended to boost motivation, elicit more naturalistic emotional responses, and enrich the behavioral and physiological data collected.

1.4 THESIS OVERVIEW

This thesis examines how adverse childhood experiences (ACEs) shape two core aspects of affective functioning: physiological reactivity and associative learning in the domains of threat and reward, and how these processes relate to behavioral patterns of avoidance. In **Chapter 2** we investigate the effects of early and recent adversities on emotional processing using the "Affective Startle Modulation" paradigm. This study examines ACEs and recent adversities influence physiological reactivity in healthy adults. Through psychophysiological measures such as skin conductance reactivity, the study explores how distinct physiological response profiles emerge based on the timing and type of adversity experienced, shedding light on different defensive response patterns. Here we identified how early and recent adversity types can "get under the skin" and manifest as time-experience-dependent (early vs recent) plasticity in sympathetic nervous system reactivity. To further investigate this, in **Chapter 3**, we conducted a systematic review of the literature focusing on how ACEs may impact the normative maturation of associative learning processes, resulting in their enduring maladaptive expression manifesting in psychopathology. This chapter also underscores the need to refine measurement methods and foster cross-laboratory collaborations to enhance our understanding of the individual risk and resilience pathways linked to . In **Chapter 4**, we build on the findings from **Chapter 2**, where physiological processing was studied through traditional methods, such as passively measuring responses to static images in a controlled setting. While these methods provided critical insights into emotional responses, **Chapter 4** introduces a new focus: the investigation of **approach-avoidance (AA) behavior** within a dynamic, immersive environment. Methodologically, this chapter extends the experimental framework by incorporating active, goal-directed behavior, where participants navigate risks and rewards in real time within a virtual foraging task. The shift from passive observation to active participation allows for a more authentic exploration of emotional processing. Participants made decisions that balance threat and reward, offering a richer and more authentic context to study behavior. By applying **gamification** in a virtual reality setting, this chapter explores how individuals manage conflicts, providing an extended perspective on how emotional and motivational systems operate in real-world scenarios. To integrate findings from the relatively isolated fields of threat and reward learning and comprehensively analyze how ACEs may be linked to associative learning, it is crucial to first understand the operational processes involved in each domain. Study II directly addresses this by offering a systematic and methodological synthesis of existing evidence on the relationship between ACEs and the mechanisms underlying both threat and reward learning, thereby bridging the gap between these two domains.

Chapter 2:

PHYSIOLOGICAL PROCESSING

Chapter 2

PHYSIOLOGICAL PROCESSING

Study 1 - Watching with Argus Eyes: Characterization of emotional and physiological responding in adults exposed to ACEs and/or recent adversity

This study is already published: Koppold, A.*, Kastrinogiannis, A.*, Kuhn, M., Lonsdorf, T. B. (2023). Watching with Argus eyes: Characterization of emotional and physiological responding in adults exposed to childhood maltreatment and/or recent adversity. Psychophysiology, 00, e14253. https://doi.org/10.1111/psyp.14253

How does exposure to early and recent adversity shape the way we process emotions? During this study, we aimed to explore the impact of the exposure to both early (during childhood) but also recent (during adulthood) adverse experiences in a sample of 685 healthy adults.

2.1 Introduction

As highlighted in Chapter 1.1, emotions play a central role in human functioning, shaping our thoughts, behaviors, social interactions, and even survival. From an evolutionary perspective, the ability to detect and respond to emotionally salient cues - especially those signaling threat - has been crucial for adaptive functioning and safety. Accurately perceiving these cues and generating appropriate physiological and behavioral responses allows individuals to navigate both social and physical environments effectively. While these emotional mechanisms are broadly adaptive, they are not fixed; rather, they are profoundly shaped by individual experiences. Importantly, these experiences are not limited to war zones or combat settings. Extreme circumstances such as terrorist attacks, forced migration, systemic oppression, and interpersonal violence can also profoundly interfere with the development of core neural systems involved in emotion regulation (McLaughlin et al., 2014; Tottenham & Galván, 2016). Moreover, individuals exposed to chronic adversity are also at elevated risk for disruptions in emotional processing and regulation (Fazel et al., 2012; Teicher & Samson, 2016; Williams & Mohammed, 2009). Building on that foundation, childhood is a uniquely sensitive period in which adversity -including maltreatment - has the potential to shape neural and emotional development, shaping enduring patterns of reactivity, regulation, and behavior with lasting implications for mental health and resilience (Oh et al., 2018; Eid et al., 2024; Grasser et al., 2024, Sheridan & McLaughlin, 2014; Milojevich et al., 2020). More specifically, research demonstrates that individuals with a history of childhood adversity exhibit increased amygdala activation and disrupted functional connectivity in brain regions associated with threat processing, such as the amygdala and prefrontal cortex, particularly in response to threatening stimuli like angry or fearful faces (McCrory et al., 2011; Stevens et al., 2017; France et al., 2022). Systematic reviews further reveal that children exposed to threat-related adversity consistently display reduced amygdala and medial prefrontal cortex volumes, and heightened amygdala activation to threat, whereas deprivation is more closely linked to altered frontoparietal function (Gee et al., 2013; Hosseini-Kamkar et al., 2023; McLaughlin et al., 2014). Exposure to interpersonal violence in youth has also been shown to alter the co-activation of the amygdala and ventromedial prefrontal cortex during unpredictable threat, underscoring the specificity of neural changes related to different forms of adversity (Bounoua et al., 2024). Complementing these neural findings, a substantial body of research demonstrates that people who have experienced childhood adversity process threat differently at the neural and behavioral levels compared to those without such backgrounds, underscoring clear differences between exposed and non-exposed groups (Pine et al., 2005; Pollak et al., 2005; Tottenham & Sheridan, 2010; Saarinen et al., 2021). However, it is important to note that the literature is not entirely uniform. Some studies, particularly those examining individuals who have experienced less severe or more transient forms of adversity - such as occasional family conflict, temporary financial strain, or isolated stressful events, rather than chronic abuse or neglect - or those focusing on high-functioning populations (i.e. strong coping skills, higher socioeconomic status), have reported no significant differences in amygdala activation between those with and without childhood adversity (Mirman et al., 2020), suggesting that factors beyond exposure severity, such as sample characteristics or methodological differences, may also contribute to these mixed results. Taken together, however, the majority of evidence suggests that individuals with a history of childhood adversity, on average, exhibit heightened sensitivity to threat and more reactive responses to potentially threatening situations, even though the specific neural correlates of these responses may vary across studies (Shackman et al., 2007). While heightened sensitivity to threat can be an adaptive response shaped by prior experiences, in some cases it may tip into maladaptive patterns that increase vulnerability to anxiety disorders, depression, and post-traumatic stress disorder (PTSD) (Gray et al., 2021; Jovanovic et al., 2005). Empirical work demonstrates that elevated threat reactivity is linked to adverse mental health outcomes, such as anxiety, depression, PTSD and problematic alcohol use, particularly when this sensitivity becomes excessive or poorly regulated. Early adversity appears to amplify this risk, as it is often associated with heightened or dysregulated threat sensitivity (Hall et al., 2022; Campbell, 2024). At the same time, resilience research highlights that adaptive coping and protective factors can buffer against these maladaptive trajectories, emphasizing the importance of identifying individuals whose adaptive responses to adversity may transition into risk states (Ungar, 2015). While the present work does not examine these mechanisms directly, they provide an important context for interpreting adversity-related outcomes and point toward future directions in identifying resilience factors and potential intervention targets. Building on this, the first study examined responses in the Affective Startle Modulation (ASM) paradigm (Lang et al., 1990; see Methods and Materials), which reliably elicits positive and negative emotions through passive exposure to pleasant, unpleasant, and neutral images that differ in arousal and valence.

Within the ASM framework,EMG startle responses are widely used as an indirect measure of motivational priming, specifically capturing the valence dimension by reflecting activation of the defensive system (Sabatinelli et al., 2001). Numerous studies have consistently demonstrated that the startle reflex is amplified during the viewing of unpleasant stimuli and attenuated during pleasant stimuli relative to neutral ones (Bradley et al., 2001; Kuhn et al., 2020; Lang et al., 1993). Importantly, heightened startle responses to aversive stimuli have been linked to anxiety disorders with specific fears, such as phobias, whereas diminished startle reactivity has been observed in conditions marked by chronic anxiety, avoidance, and comorbid depression, including PTSD with multiple trauma histories and generalized anxiety disorder (Cuthbert et al., 2003). At the same time, even though heightened startle responses are typically associated with PTSD, individuals with PTSD following childhood maltreatment have shown blunted startle responses to threat cues (i.e., CS+) during fear conditioning tasks (Lis et al., 2020). Research on PTSD populations has yielded mixed findings: while some early studies in veterans reported elevated startle responses (Morgan, 1996), others observed blunted responses (Grillon et al., 1996). Among individuals without psychiatric diagnoses, trauma exposure has been associated with increased startle reactivity, particularly in those reporting high levels of physical or sexual abuse (Jovanovic et al., 2009; Medina et al., 2001), and in individuals exposed to life-threatening events before age 14 (Pole, 2007). At the same time, evidence indicates that different forms and contexts of adversity can lead to opposite outcomes, with some studies reporting attenuated startle responses in adolescents and young boys with histories of neglect or maltreatment (Klorman et al., 2003; Quevedo et al., 2015). A large-scale longitudinal study in marines reported reduced anticipatory startle responses in those with childhood adversity when anticipating negative but not positive stimuli, though with small effect sizes, while recent deployment trauma was linked to elevated startle across emotional contexts (Stout et al., 2021). Overall, the field lacks integrative studies focusing on valence-specific response patterns related to early and recent adversity in nonclinical populations, as most prior work has focused on clinical samples (e.g., patients with anxiety or PTSD) or other high-risk groups (e.g., maltreated youth, combat veterans, foster care populations; Klorman et al., 2003; McTeague & Lang, 2012; Quevedo et al., 2015; Stout et al., 2021). By investigating these processes in a healthy adult sample, the present study presented in this thesis contributes to addressing this gap.

In parallel, SCR, reflecting sympathetic nervous system activation, have been shown to track arousal rather than valence, with heightened responses to both positive and negative emotional material (Boucsein, 2012; Bradley et al., 2001; Kuhn et al., 2020; Lang et al., 1993). Interestingly, children exposed to maltreatment often show globally reduced SCRs during emotional and cognitive tasks (Carrey et al., 1995), as well as impaired discrimination between safety and threat cues in fear conditioning (McLaughlin et al., 2016). Recent work has also linked peer victimization and early adversity to diminished SCRs, both generally and in response to pain stimuli (Iffland et al., 2014a; You & Meagher, 2016), although some findings suggest that individuals with subclinical trauma symptoms or less severe exposure display heightened SCRs (D'Andrea et al., 2013; Pole, 2007). Prior research by the current group similarly reported reduced SCRs to conditioned danger cues following recent adversity (Scharfenort et al., 2016).

This pre-registered study (`https://osf.io/8kmgw/`) aimed to deepen the understanding of how early and recent adversity shape emotional processing in a large nonclinical sample (n = 685). For the main effect of task, we anticipated that EMG startle responses and skin conductance responses (SCRs) would follow their characteristic modulation patterns by valence and arousal, respectively, thereby replicating the well-established task effects in affective modulation paradigms (Kuhn et al., 2020; Lang et al., 1990). Additionally, we hypothesized:

- **General blunting of physiological responses:** Individuals with histories of childhood and recent adversity will display reduced physiological reactivity in both EMG startle and SCR measures (main effect of adversity).
- **Blunted reactivity to negative stimuli:** Adversity-exposed individuals would show particularly diminished physiological responses to negative stimuli, compared to positive or neutral stimuli, across both EMG and SCR measures.

Additionally, we aimed to replicate earlier findings of increased trait anxiety and depression among individuals exposed to both childhood and recent adversity compared to non-exposed peers (Kuhn et al., 2016). Although these hypotheses were pre-registered, we acknowledge that the heterogeneity of previous findings could have supported alternative predictions, as noted by a reviewer (see discussion). As part of our pre-registered exploratory analyses, we also examined subtypes of childhood maltreatment (e.g., threat vs. deprivation; emotional vs. physical abuse) and evaluated the concordance between two widely used assessment instruments - the Childhood Trauma Questionnaire (CTQ; Bernstein et al., 2003) and the German Maltreatment and Abuse Chronology of Exposure questionnaire (KERF;Isele et al., 2014). While no formal hypotheses were specified for these exploratory analyses, we recognize that predictions could - in principle - have been drawn from prior research, as also noted in the discussion.

2.2 Methods and Materials

Subjects

The final sample comprised 685 participants (424 women, 246 men; mean age ± SD: 24.93 ± 4.93 years for women, 26.40 ± 5.82 years for men), drawn from four combined sub-studies. Eligibility criteria included being physically and mentally healthy, aged between 18 and 50 years, and self-identifying as of Caucasian descent. Individuals were excluded if they were currently taking medication (with the exception of oral contraceptives), had a lifetime history of psychiatric disorders, or were pregnant. All participants had normal or corrected-to-normal vision. Written informed consent was obtained from all participants, and the study protocol was approved by the Ethics Committee of the General Medical Council Hamburg (PV 2755), in accordance with the Declaration of Helsinki. A total of 485 participants completed both primary questionnaires assessing childhood adversity (CTQ and KERF). The study sample was pooled from four sub-tudies that used identical tasks, settings, and equipment, with most participants drawn from a large multi-year project and additional participants from smaller related studies.

Experimental Design

The experimental setup involved an affective startle modulation task (see introduction), starting with a habituation phase for the startle response, followed by the passive viewing of 36 images representing various emotional tones (negative, neutral, and positive). Each image was shown twice, amounting to a total of 72 trials. For the positive category, erotic images were selected based on the participant's sexual orientation, while the negative images portrayed scenes perceived as personally threatening. Each image appeared on the screen for 6 seconds, with random inter-trial intervals of 10 to 14 seconds. Startle probes were administered in half of the trials, either 4.5 or 5.5 seconds after the image appeared. After the task, participants rated the emotional valence and arousal of the images using the Self-Assessment Manikin scale.

Collection and Processing of Psychophysiological Data

Physiological measures - including startle eye-blink EMG and SCR - were gathered using a BIOPAC MP100 (BIOPAC Systems Inc.) system combined with AcqKnowledge software. Because data were acquired in multiple lab rooms (albeit with matching equipment and protocols), raw signal outputs showed variation in scale. To correct for these discrepancies, participant-level normalization was applied using z-score standardization.

Skin Conductance Measurement

To measure SCR, self-adhesive Ag/AgCl electrodes were attached to the palm of the left hand, specifically over the distal and proximal hypothenar regions. Recordings were made at a sampling frequency of 1,000 Hz with a gain setting of 5 µΩ. After data collection, signals were downsampled to 10 Hz. A custom software tool was used to semi-automatically score SCR amplitudes, and individual differences were normalized using z-scores.

Electromyography Measurement

EMG data capturing the startle eye-blink reflex were recorded using electrodes positioned above and below the left eye. Data were collected at 2,000 Hz, noise-filtered, and downsampled offline to 10 Hz. Amplitude scoring was carried out semi-automatically using custom software, focusing on peak-to-peak measurements within a 50 ms window following the onset of the startle stimulus.

Survey Instruments

The German version of the *Childhood Trauma Questionnaire* (CTQ; Wingenfeld et al., 2010) evaluates adverse childhood experiences across five domains - emotional, physical, and sexual abuse, along with emotional and physical neglect - using 28 items rated on a five-point scale until the age of 18 (Bernstein et al., 2003). Of these, 25 items are scored on a five-point scale and contribute to subscale scores (range 5-25; total score 25-125), while three minimization/denial items are evaluated separately to detect potential underreporting. In addition to these categorical classifications, total and subscale sum scores were retained as continuous indices of adversity severity. Individuals surpassing the moderate-to-severe threshold on any subscale - emotional abuse (≥13), physical abuse (≥10), sexual abuse (≥8), emotional neglect (≥15), or physical neglect (≥10) - were categorized as exposed (Häuser et al., 2011; provides German CTQ version details, cutoffs, and analysis guidelines). The CTQ has demonstrated strong measurement properties, including strong internal consistency, reliability, and structural validity (Saini et al., 2019). The *Maltreatment and Abuse Chronology of Exposure* (MACE; German name: KERF) questionnaire (Isele et al., 2014) assesses childhood adversity through 75 items divided across ten subscales. It uses yes–no responses and collects details on the age of occurrence, perceived helplessness, and fear. Participants were classified as exposed if they endorsed at least one qualifying item on any KERF subscale, which cover domains such as parental physical, verbal, and nonverbal emotional violence; emotional and physical neglect; witnessed violence toward parents or siblings; and peer-related emotional, physical, or sexual violence. As with the CTQ, total and subscale scores were also considered in their continuous form to capture severity across adversity domains. The KERF scores align well with CTQ sum scores, and evidence from the English MACE version indicates strong psychometric properties, including excellent test–retest reliability for total, multiplicity, and subscale scores (Schalinski et al., 2016; Teicher, 2015). The *List of Threatening Experiences* (LTE; (T. Brugha et al., 1985; T. S. Brugha & Cragg, 1990) captures exposure to 12 categories of stressful events over the past year via yes-no questions. Participants reporting at least one event are considered exposed. The LTE has demonstrated high stability over time (test-retest reliability) and low internal consistency (Motrico et al., 2013). The *Spielberger Trait Anxiety Inventory* (STAI-T; Spielberger, 2012) assesses relatively stable tendencies toward negative affect—but not specifically anxiety—with 20 items rated on a four-point Likert scale. The STAI-T has demonstrated high internal consistency and moderate-to-high test–retest reliability (Klingelhöfer-Jens et al., 2025) but meta-analytic evidence suggests that describing it as a measure of ‘trait anxiety’ may be a misnomer and that it is better conceptualized as a non-specific measure of negative affectivity

(Knowles & Olatunji, 2020). The *Beck Depression Inventory* (BDI; Beck, 1961) measures depression severity using 21 items on four- or five-point scales, with reference to symptoms experienced over the past two weeks, including the day of assessment. The BDI-II version has shown excellent consistency and reliability across adolescent and adult populations, both clinical and non-clinical, and has demonstrated adequate sensitivity and specificity for diagnostic screening (García-Batista et al., 2018; Gomes-Oliveira et al., 2012; Kojima et al., 2002; Segal et al., 2008).

Statistical Analyses

Analyses were performed using linear mixed-effects models, with childhood adversity scores as predictors and affective startle modulation as the outcome. The dataset included 485 participants who completed both main childhood adversity questionnaires. To examine the effects of emotional valence (negative, neutral, positive) on SCR and EMG startle measures, models used valence as the independent variable and the physiological responses as dependent variables. Childhood maltreatment (CM) and recent adversity (RA) were then incorporated as predictors, and interactions were tested using z-standardized outcome variables. All models included random intercepts for subjects. Wilcoxon tests were used for post hoc pairwise comparisons.

The impact of CM and RA on symptom scores (STAI, BDI) was evaluated using two-way ANOVAs with interaction terms, as only one data point per participant was available. Additional exploratory analyses investigated adversity subtypes (e.g., threat vs. deprivation, emotional vs. physical adversity), operationalized according to the CTQ subscales as described above (see CTQ description). Agreement between CTQ and KERF classification was assessed using Cohen's Kappa for categorical outcomes and the intraclass correlation coefficient (ICC) for continuous scores, with ICCs computed from mean values due to differences in subscale lengths. Analyses and visualizations were conducted in R (version 4.2.2; RStudio Team, 2021).

Robustness Analysis

Previous research indicates that excluding non-responders may artificially reduce variability and obscure group differences in physiological reactivity (Lonsdorf et al., 2019). Therefore, the main analyses included all participants, but robustness was assessed by reanalyzing the data after removing non-responders (results not reported here). Participants were classified as non-responders if they exhibited more than two-thirds missing data (due to recording artifacts or signal loss) or no measurable responses (0.00 µS) across all valence conditions (negative, neutral, positive), following Lonsdorf et al. (2019).

2.3 Results

Sample Descriptives

The complete sample included 246 men and 424 women, with an average age of 25.36 years (mean age ± SD: females 24.93 ± 4.93; males 26.40 ± 5.82). Among the participants, 124 individuals (19.05%) were identified as having experienced childhood maltreatment, while 527 (80.95%) were classified as non-exposed. Regarding recent adversity, 167 participants (25.57%) were categorized as exposed, and 486 (74.43%) as not exposed. Those who had experienced childhood adversity were significantly older compared to those without such experiences (t(649) = 4.12, p < .01), though no sex differences were observed. In contrast, no significant age or sex differences were found between those exposed and not exposed to recent adversity. For further details, including participants' educational and employment background, refer to Table 1. All analyses reported in this study included participants regardless of physiological non-responder status.

Main effect of task

As expected from previous work, a significant main effect of picture valence was observed in both EMG: F(2, 20,077) = 268.48, p =< .001 (negative > neutral > positive, all pairwise comparisons p < .001); and SCR: F(2, 37,505) = 65.78, p =< .001 (negative > positive > neutral, all pairwise comparisons p < .002) with EMG responses following the expected valence gradient and SCR responses following the expected arousal gradient.

Effect of Childhood Maltreatment and Recent Adversity on Anxiety and Depression Scores

Consistent with our expectations, we confirmed earlier findings showing that individuals with a history of childhood maltreatment and recent adversity (CM+, RA+) exhibit significantly elevated levels of trait anxiety (all p's < .01, Figure 3a,b) and depression (all p's < .01, Figure 3c,d) compared to those without such experiences (CM−, RA−). Notably, no interaction effect was observed between childhood and recent adversity (F(1,644)=0.0005, p=0.98; BDI: F(1,481)=1.50, p=.22).

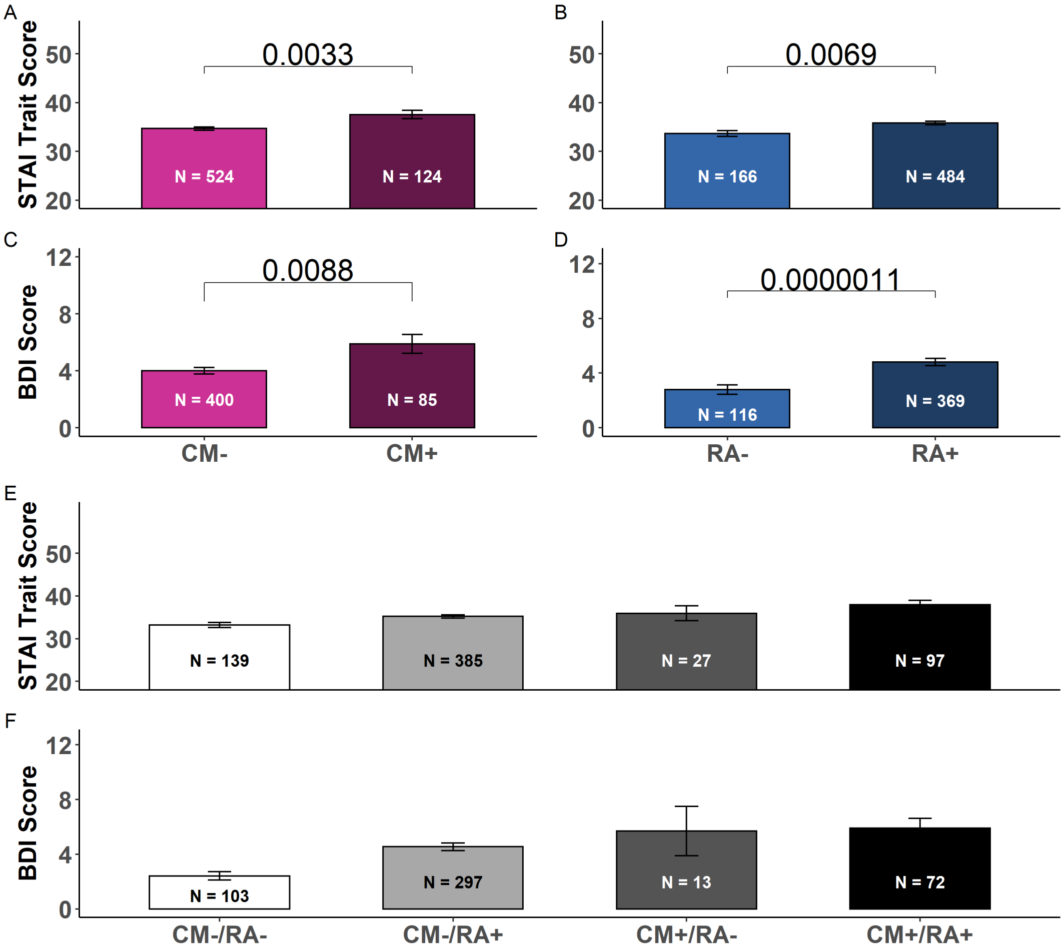
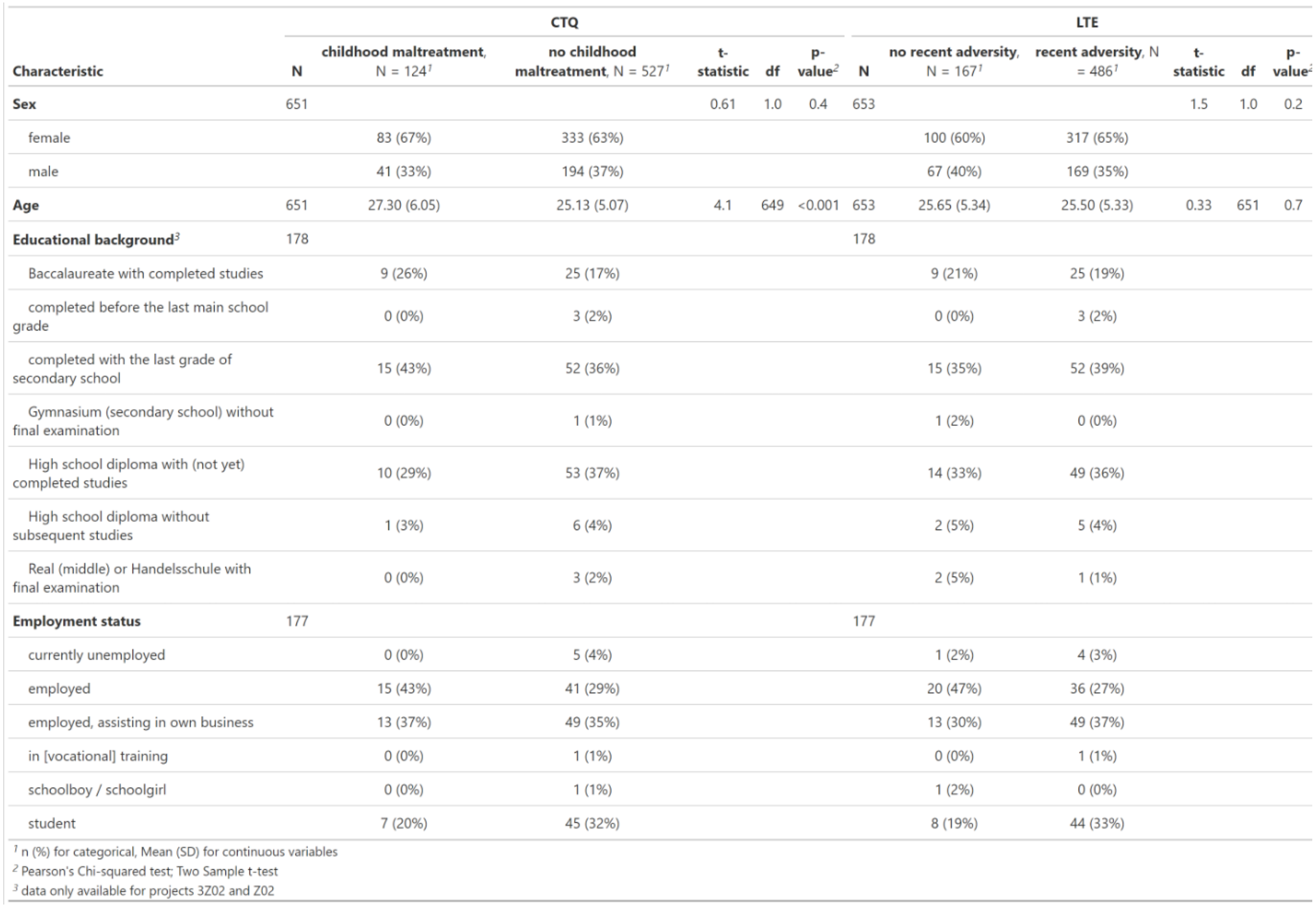


Figure 3: Trait anxiety (A,B, E) and depression (C,D, F) scores for individuals exposed to childhood (A,C) and recent adversity (B,D) as well as their combination (E,F). The figure illustrates that we observe a main effect of CA on both anxiety and depression as well as a main effect of RA on both anxiety and depression (A-D) but no interaction (E,F). Error bars represent SEM. Asterisks indicate statistical significance, *** P < 0.001; ** P < 0.01; * P < 0.05 derived from an ANOVA as described in the results.



Characteristic	N	childhood maltreatment, N = 124[1]	no childhood maltreatment, N = 527[1]	t-statistic	df	p-value[2]	N	no recent adversity, N = 167[1]	recent adversity, N = 486[1]	t-statistic	df	p-value[2]
		CTQ						LTE				
Sex	651			0.61	1.0	0.4	653			1.5	1.0	0.2
female		83 (67%)	333 (63%)					100 (60%)	317 (65%)			
male		41 (33%)	194 (37%)					67 (40%)	169 (35%)			
Age	651	27.30 (6.05)	25.13 (5.07)	4.1	649	<0.001	653	25.65 (5.34)	25.50 (5.33)	0.33	651	0.7
Educational background[3]	178						178					
Baccalaureate with completed studies		9 (26%)	25 (17%)					9 (21%)	25 (19%)			
completed before the last main school grade		0 (0%)	3 (2%)					0 (0%)	3 (2%)			
completed with the last grade of secondary school		15 (43%)	52 (36%)					15 (35%)	52 (39%)			
Gymnasium (secondary school) without final examination		0 (0%)	1 (1%)					1 (2%)	0 (0%)			
High school diploma with (not yet) completed studies		10 (29%)	53 (37%)					14 (33%)	49 (36%)			
High school diploma without subsequent studies		1 (3%)	6 (4%)					2 (5%)	5 (4%)			
Real (middle) or Handelsschule with final examination		0 (0%)	3 (2%)					2 (5%)	1 (1%)			
Employment status	177						177					
currently unemployed		0 (0%)	5 (4%)					1 (2%)	4 (3%)			
employed		15 (43%)	41 (29%)					20 (47%)	36 (27%)			
employed, assisting in own business		13 (37%)	49 (35%)					13 (30%)	49 (37%)			
in [vocational] training		0 (0%)	1 (1%)					0 (0%)	1 (1%)			
schoolboy / schoolgirl		0 (0%)	1 (1%)					1 (2%)	0 (0%)			
student		7 (20%)	45 (32%)					8 (19%)	44 (33%)			

[1] n (%) for categorical, Mean (SD) for continuous variables

[2] Pearson's Chi-squared test; Two Sample t-test

[3] data only available for projects 3Z02 and Z02

Table 1. Detailed overview of participant's descriptives based on exposure (vs. non-exposure) to childhood adversity (as assessed by the CTQ) and recent adversity (as assessed by the LTE).

When examining continuous scores, we found a significant positive association between adversity exposure and both anxiety (CM: r = .23, p < .001; RA: r = .18, p < .001, Figure 4a,b) and depression (CM: r = .21, p < .001; RA: r = .27, p < .001, Figure 4c,d), suggesting that greater exposure is linked to higher anxiety and depression levels.

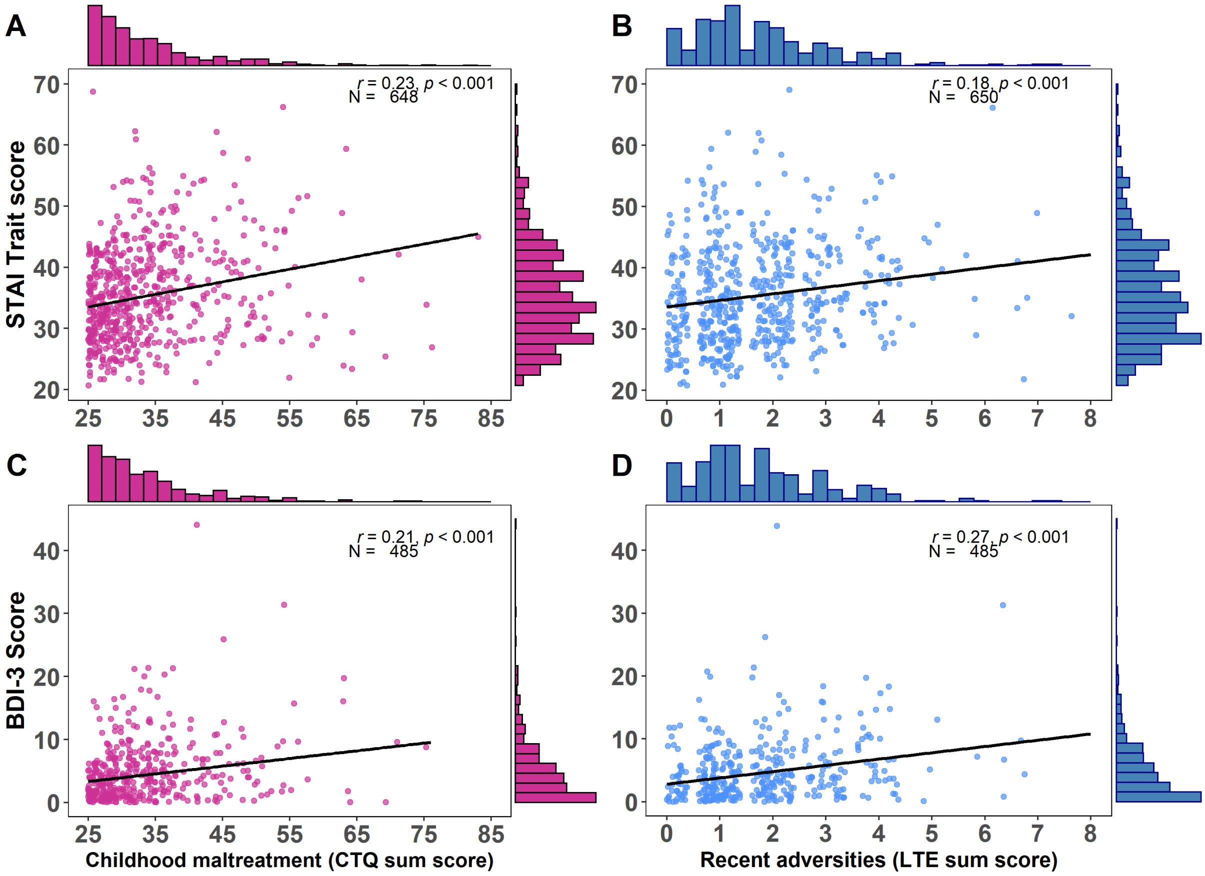


Figure 4: Scatterplots with marginal histograms displaying the relationships between continuous measures of childhood maltreatment (a, c) and recent adversity (b, d) and their associations with trait anxiety (a, b) and depression (c, d) scores. The plots include Pearson correlation coefficients (r) and sample sizes. According to Spielberger (2012), anxiety scores are typically categorized as low (20–39), moderate (40–59), and high (60–80), while depression severity is classified as minimal (0–13), mild (14–19), moderate (20–28), and severe (29–63) based on total scores.

Primary effects of childhood maltreatment and recent adversity on psychophysiological responses

Contrary to our hypothesis, recent adversity was linked to increased SCRs (F(1, 509) = 7.39, p = .0068; Fig. 5e), even among responders only (F(1, 268) = 5.51, p = .02). Childhood maltreatment showed no main effect on SCRs (F(1, 509) = 2.89, p = .09; Fig. 5d). Neither childhood maltreatment nor recent adversity significantly affected EMG responses (CM: F(1, 566) = 1.62, p = .2; Fig. 5a; RA: F(1, 566) = 0.02, p = .89; Fig. 5b), and no interaction effects were found for EMG or SCRs (EMG: F(1, 566) = 0.02, p = .89; Fig. 5c; SCRs: F(1, 509) = 0.82, p = .37; Fig. 5f).

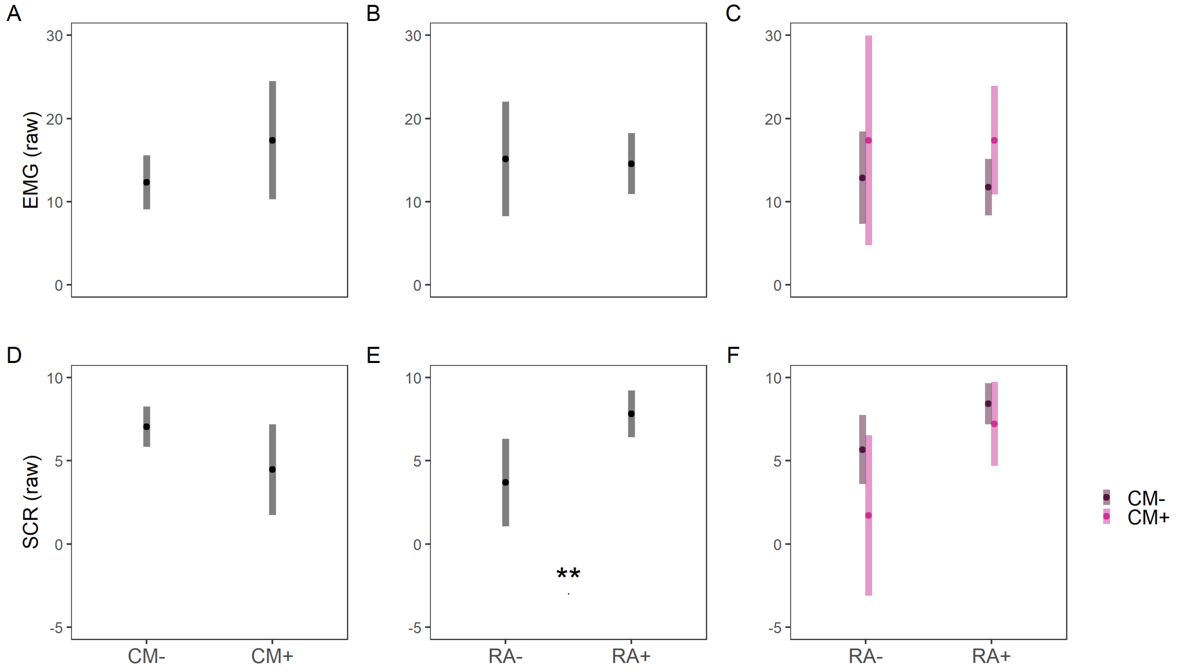


Figure 5: Estimated marginal means and 95% confidence intervals for raw startle eyeblink magnitude (a–c) and raw skin conductance response amplitudes (d–f), shown for participants with and without childhood maltreatment exposure (a, d), recent life adversity exposure (b, e), and the combined effects of both (c, f).

Interaction between childhood maltreatment, recent adversity, and picture valence

We found notable interactions between childhood maltreatment and picture valence, as well as between recent life adversity and picture valence, when analyzing SCRs (childhood maltreatment: F(2, 36,155) = 4.04, p = .018; recent adversity: F(2, 36,155) = 7.27, p ≤ .001; see Figure 6b), but not in EMG activity (CM: F(2, 19,511) = 0.10, p = .91; RA: F(2, 19,511) = 1.31, p = .27; see Figure 6a). These interactions were largely driven by responses to neutral images rather than, as initially predicted, to negative ones. Specifically, participants with a history of childhood maltreatment showed reduced SCRs to neutral images and heightened responses to negative images (see Table 2a for post hoc results). Participants who had recently experienced adversity displayed a stronger differentiation in SCRs between negative and neutral images. This pattern emerged because those without recent adversity showed similar response levels to both image types, whereas those exposed to recent adversity reacted more strongly to negative images compared to neutral ones (post hoc details in Table 2b). However, these effects were not consistent when the analysis was limited to “responders only”, so these results should be interpreted cautiously.

It’s also important to highlight that females were significantly overrepresented among non-responders ($\chi^2(1, 383) = 33.95$, $p < .001$; see Table 1). For SCR non-responders, individuals with childhood maltreatment were somewhat more common, though not significantly so ($\chi^2(1, N = 685) = 2.83$, $p = .09$). In contrast, for EMG non-responders there was no difference at all between groups ($\chi^2(1, N = 586) = 0.00$, $p = 1.00$). This uneven distribution may partly explain the differing results, particularly given that neutral, low-arousal images generally elicit smaller amplitude responses. Notably, removing non-responders reduced the sample size substantially - from N = 586 to N = 539 for EMG, and from N = 532 to N = 272 for SCR - resulting in a considerable loss of statistical power, especially for the SCR data.

Additionally, a significant three-way interaction between childhood maltreatment, recent adversity, and picture valence was detected in SCRs ($F(2, 36{,}155) = 4.78$, $p = .0084$), but not in EMG ($F(2, 19{,}511) = 0.70$, $p = .5$). Individuals with a history of childhood maltreatment but no recent adversity (CM+, RA−) exhibited the strongest discrimination between negative and neutral images in SCRs compared to all other groups (see Table 1 and Figure 7). Nevertheless, we advise caution when interpreting this result because the CM+, RA− group was quite small (N = 27) relative to the other groups (which ranged from N = 97 to 387).

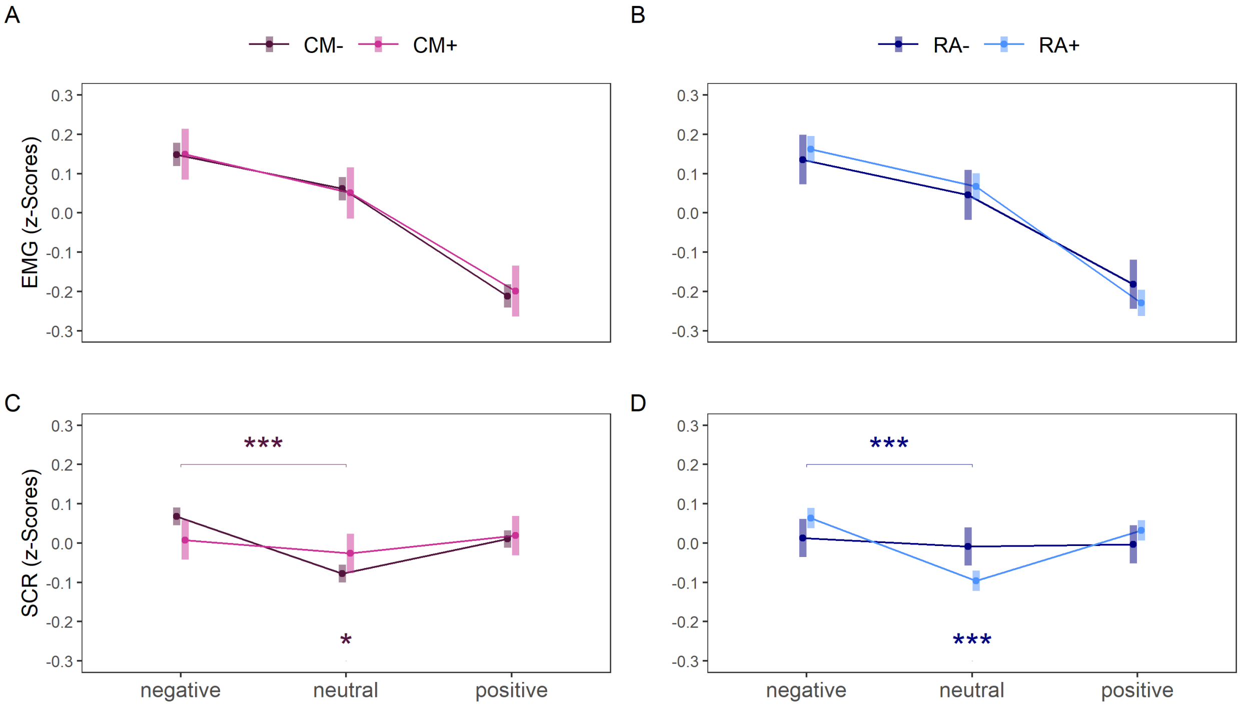


Figure 6: Estimated marginal means (calculated from z-standardized amplitudes) and corresponding 95% confidence intervals are presented for startle eyeblink magnitude (panels a, b) and skin conductance responses (panels c, d) across images with negative, neutral, and positive emotional content, separately for participants with a history of childhood maltreatment (a, c) and those with recent life adversity (b, d).

Table 2A: Post-hoc pairwise comparisons for the interaction between childhood maltreatment (CM+ / CM-) and picture valence (positive, neutral, negative) in SCR.

Contrast	Estimate	SE	z	p.value
No CM negative – CM negative	0.06	0.03	2.15	0.263
No CM positive – CM positive	-0.01	0.03	-0.31	1.000
No CM neutral – CM neutral	-0.05	0.03	-1.84	0.441
No CM negative – No CM neutral	0.15	0.02	8.99	0.001
No CM negative – No CM positive	0.06	0.02	3.56	0.005
No CM neutral – No CM positive	-0.09	0.02	-5.43	0.001
CM negative – CM neutral	0.03	0.04	0.94	0.935
CM negative – CM positive	-0.01	0.04	-0.31	1.000
CM neutral – CM positive	-0.05	0.04	-1.25	0.813

Table 2B: Post-hoc pairwise comparisons for the interaction between recent adversity (RA+ / RA-) and picture valence (positive, neutral, negative).

Contrast	Estimate	SE	z	p.value
No RA negative – RA negative	-0.05	0.03	-1.81	0.458
No RA positive – RA positive	-0.04	0.03	-1.29	0.793
No RA neutral – RA neutral	0.09	0.03	3.10	0.024
No RA negative – No RA neutral	0.02	0.04	0.61	0.991
No RA negative – No RA positive	0.02	0.04	0.46	0.998
No RA neutral – No RA positive	-0.01	0.04	-0.15	1.000
RA negative – RA neutral	0.16	0.02	8.50	0.001
RA negative – RA positive	0.03	0.02	1.64	0.574
RA neutral – RA positive	-0.13	0.02	-6.86	0.001

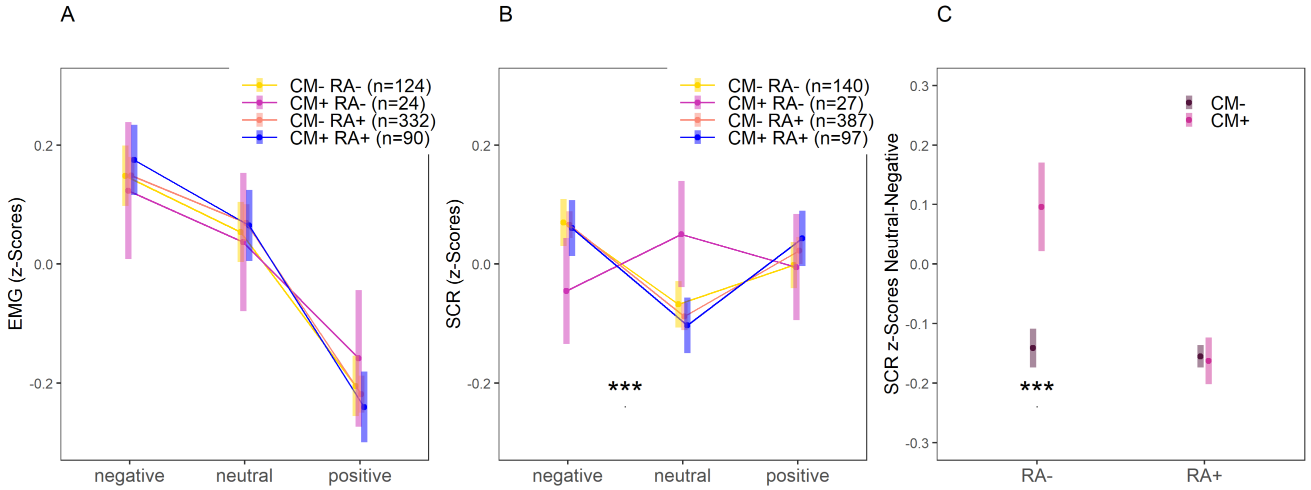


Figure 7: Estimated marginal means (derived from z-standardized amplitudes) and 95% confidence intervals for affective modulation in startle eyeblink magnitude (A) and skin conductance responses (B) are shown for images with negative, neutral, and positive emotional valence, across groups defined by different combinations of childhood maltreatment (CM) and recent life adversity (RA) exposure.

Associations between picture valence, arousal ratings, childhood maltreatment (CM), and recent adversity (RA)

The linear mixed-effects models showed, as expected, a strong main effect of picture valence on how participants rated valence (F(2, 18,915) = 6262, p < .001). Additionally, for valence ratings, there was a significant interaction between recent adversity (RA) and picture valence (F(2, 18,915) = 1.77, p = .17, see Figure 8b), primarily influenced by negatively valenced images. Specifically, post hoc pairwise comparisons revealed that participants with recent adversity experiences judged negative images as notably more unpleasant compared to those without such experiences (p = .02).

There was also a significant interaction between childhood maltreatment (CM) and picture valence (F(2, 18,915) = 3.73, p = .024, Figure 8a). However, when comparing groups across each valence level, no statistically meaningful differences emerged (all p’s > .14). Moreover, a significant three-ay interaction was identified between CM, RA, and picture valence (F(2, 18,915) = 10.82, p < .001, not shown), again driven by responses to negative and positive images. More precisely, participants exposed to both CM and RA (CM+, RA+) perceived negative pictures as more aversive compared to those with CM but without RA exposure (CM+, RA−; p = .04). Furthermore, those with both childhood and recent adverse experiences (CM+, RA+) rated positive pictures as less unpleasant compared to those with RA but no CM history (CM−, RA+; p = .01). It’s worth noting, however, that these findings should be interpreted cautiously, as the group displaying distinct response patterns (CM+, RA−) was relatively small (N = 23) compared to the other groups (ranging from N = 81–315). When looking at arousal ratings, a significant main effect was found for picture valence (F(2, 18,893) = 2008, p < .001), as well as a main effect of childhood maltreatment (F(1,

5250) = 5.68, p = .017, Figure 8c). Individuals with a history of CM consistently rated pictures as more arousing across all valence types than those without such history.

Lastly, no significant interaction emerged between picture valence and RA (F(2, 18,893) = 1.75, p = .17; Figure 8d), nor was there evidence of a three-way interaction (F(2, 18,893) = 1.29, p = .28).

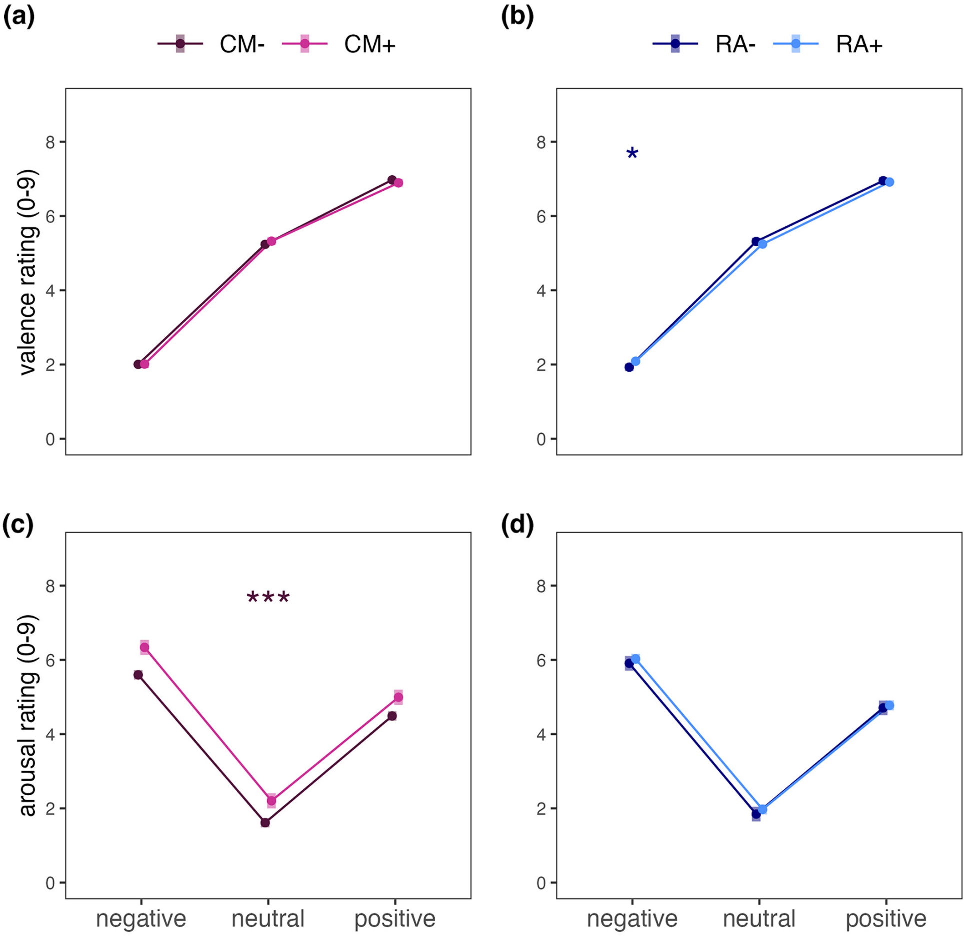


Figure 8: Estimated marginal means along with the 95% confidence intervals for picture valence ratings (a, b) and picture arousal ratings (c, d) across three valence groups and different adversity conditions (CM+: childhood maltreatment; CM−: no childhood maltreatment; RA−: no recent adversity; RA+: recent adversity). The ratings were collected using a 9-point Self-Assessment Manikin scale, where valence was rated from 1 (very pleasant) to 9 (very unpleasant) and arousal from 1 (very calm) to 9 (very stimulating). Notably, the 95% confidence intervals are very narrow.

Exploratory analyses considering childhood adversity subtypes

Additional analyses that examined various forms of childhood adversity found no notable effects on emotional modulation but did uncover some links related to general reactivity. Specifically, a significant main effect emerged for physical adversity on SCR, F(1, 509.81) = 4.1, p = .04, indicating that individuals with a history of physical abuse during childhood showed heightened overall responses compared to those without such experiences (see Figure 9d).

Regarding EMG, a significant interaction was detected between the threat (sexual, physical and emotional abuse) and deprivation (physical and emotional neglect) dimensions in relation to general reactivity F(1, 569) = 5.7, p = .02, though none of the pairwise comparisons reached significance p < .05. This interaction was mainly due to reduced EMG activity in participants exposed to threatening events relative to those unexposed, specifically among individuals who had not experienced deprivation (see Figure 9a). No additional main effects (including those for threat, deprivation, physical, or emotional maltreatment) or interactions between adversity types were identified (all p-values > 0.1), and no interactions were found with affective modulation.

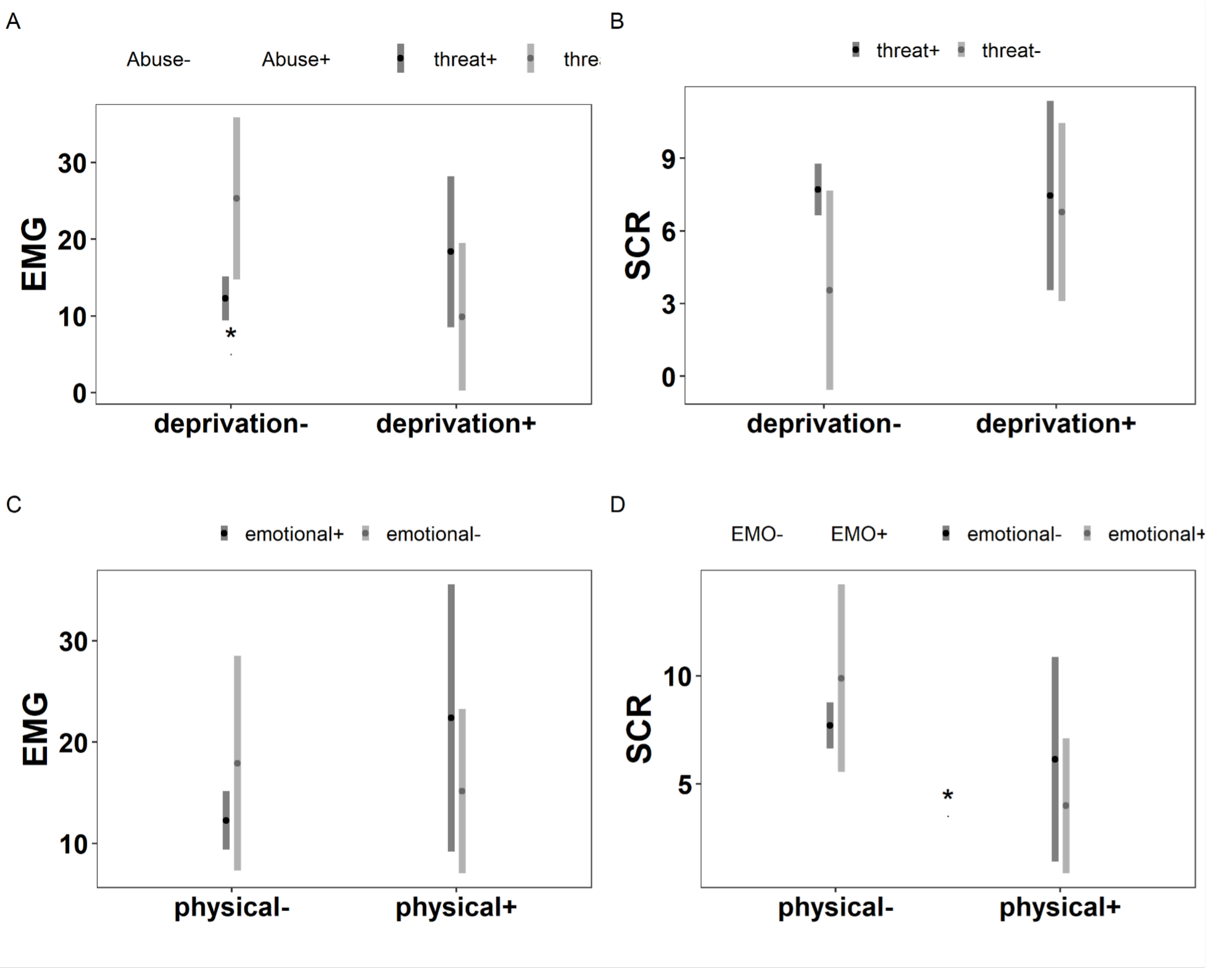
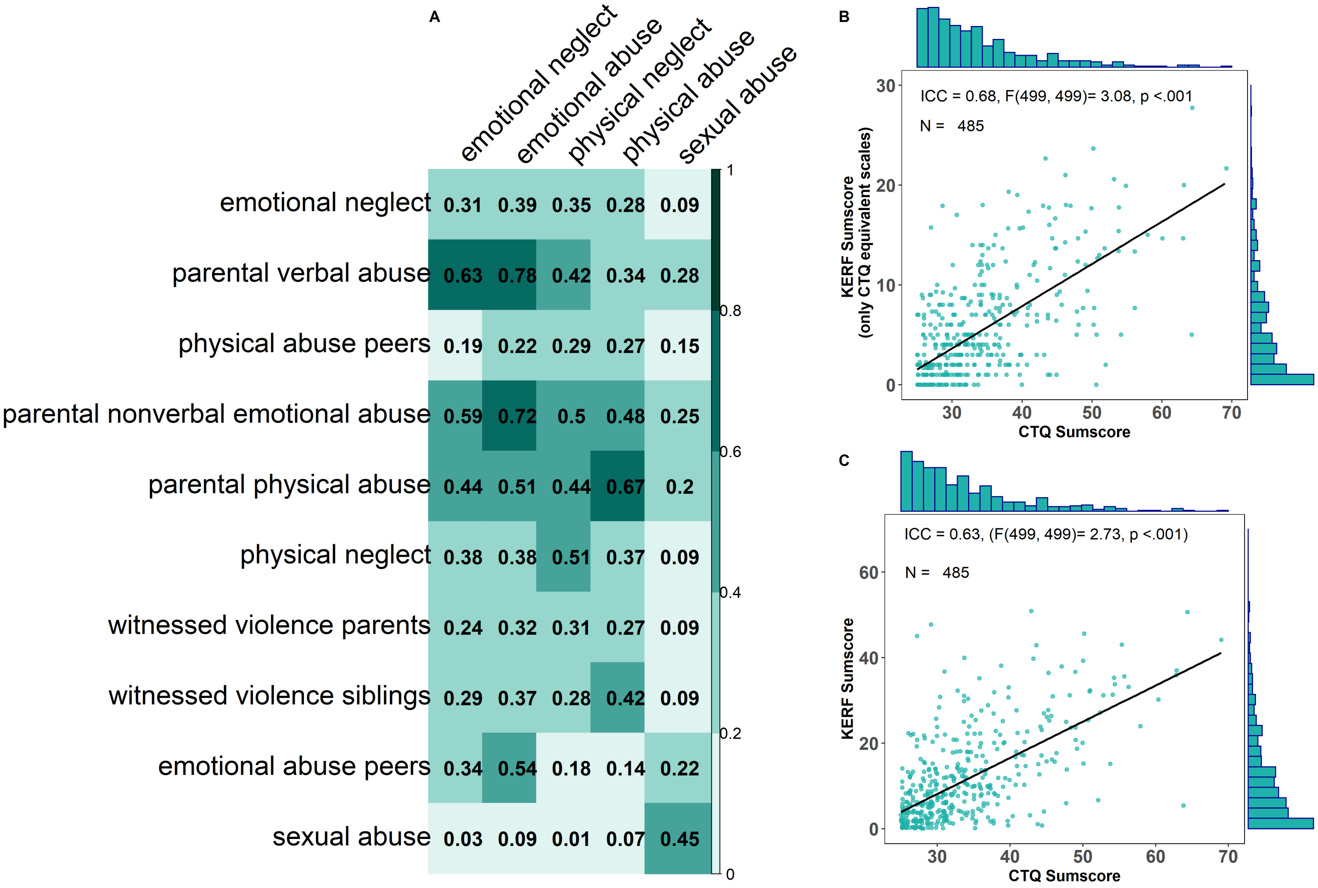


Figure 9: Estimated marginal means (raw amplitudes) along with 95% confidence intervals for general reactivity, depicted through startle eye-blink magnitude (A) and skin conductance response (B), in relation to emotional and physical childhood maltreatment.

Agreement between classifications of exposure to childhood maltreatment using two different questionnaires

The two questionnaires (CTQ and KERF) showed moderate agreement in identifying individuals as either exposed or unexposed to childhood maltreatment, with an unweighted Cohen's Kappa of κ = 0.39. Specifically, both the CTQ and KERF consistently categorized 309 individuals as unexposed and 63 individuals as exposed. However, there were discrepancies: 91 individuals were labeled unexposed by the CTQ but classified as exposed by the KERF, while 22 were marked as exposed by the CTQ but as unexposed by the KERF. Overall, the total scores from the CTQ and KERF demonstrated moderate consistency (see Figure 10b,c). Additionally, for reference and to inform future research, agreement across the various subscales of the two instruments is presented in Figure 10a.

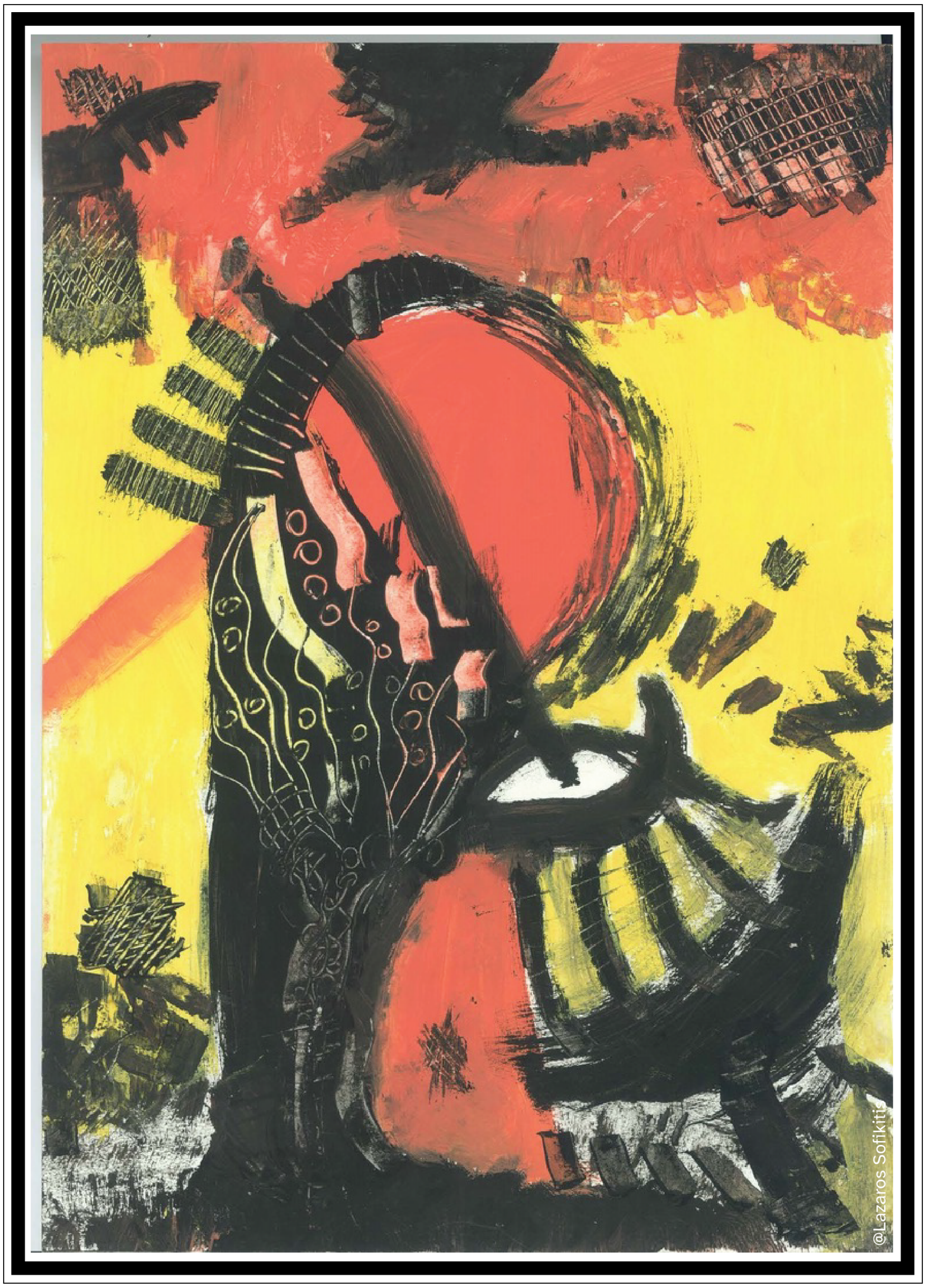


	emotional neglect	emotional abuse	physical neglect	physical abuse	sexual abuse
emotional neglect	0.31	0.39	0.35	0.28	0.09
parental verbal abuse	0.63	0.78	0.42	0.34	0.28
physical abuse peers	0.19	0.22	0.29	0.27	0.15
parental nonverbal emotional abuse	0.59	0.72	0.5	0.48	0.25
parental physical abuse	0.44	0.51	0.44	0.67	0.2
physical neglect	0.38	0.38	0.51	0.37	0.09
witnessed violence parents	0.24	0.32	0.31	0.27	0.09
witnessed violence siblings	0.29	0.37	0.28	0.42	0.09
emotional abuse peers	0.34	0.54	0.18	0.14	0.22
sexual abuse	0.03	0.09	0.01	0.07	0.45

Figure 10: Matrix of intraclass correlation coefficients (ICC consistency) illustrating the relationship between subscale scores from the CTQ (shown horizontally) and the KERF (shown vertically), with color coding reflecting the degree of consistency (0 = unacceptable, 0–0.5 = poor, 0.5–0.75 = moderate, 0.75–0.9 = good, 0.9–1 = excellent). Panels (b) and (c) present scatterplots displaying the agreement between KERF and CTQ sum scores: (b) KERF sum scores limited to subscales equivalent to those in the CTQ (sexual abuse, parental nonverbal emotional abuse, parental physical abuse, physical neglect, emotional neglect), and (c) KERF overall sum score including all KERF scales. Subscale and sum scores are calculated as means to account for differences in the number of items per scale. Each point in the scatterplots represents an individual, and the corresponding ICC consistency values are provided.

Chapter 3:

THREAT AND REWARD LEARNING



Chapter 3

THREAT AND REWARD LEARNING

Study 2 - How adverse childhood experiences get under the skin: A systematic review, integration and methodological discussion on threat and reward learning mechanisms

This study is already published: Ruge, J., Ehlers, M. R., Kastrinogiannis, A., Klingelhöfer-Jens, M., Koppold, A., Abend, R., and Lonsdorf, T. B. (2024). How adverse childhood experiences get under the skin: A systematic review, integration and methodological discussion on threat and reward learning mechanisms. eLife, 13, `e92700.https://doi.org/10.7554/eLife.92700`

How do adverse childhood experiences (ACEs) shape threat and reward learning, and what challenges remain for understanding their link to psychopathology? In this review, we explore how ACEs disrupt learning processes related to threat and reward, contributing to mental health risks, and highlight key challenges and future directions for advancing research in this field.

3.1 Introduction

Chapter 2 suggested that early and recent adversity may be linked to distinct emotional and physiological response patterns. An open question is how these experiences might influence learning processes involved in reward approach and threat avoidance.
ACEs such as abuse, neglect, or witnessing violence, disrupt the stable environments children need to grow and adapt (McLaughlin, 2016; Anda et al., 2006). These experiences are not only common - affecting around 60% of children and adolescents worldwide (Madigan et al., 2023) - but also carry long-lasting consequences, increasing the risk for mental and physical health problems and burdening healthcare systems (Felitti, 2002; Hughes et al., 2021). To understand why some individuals struggle while others are resilient, we need to look beyond the surface of symptoms and examine the underlying mechanisms through which adversity shapes development. One promising clue lies in how ACEs alter associative learning - the basic process through which

we come to expect good or bad outcomes from our environment. From early on, humans learn that some cues signal danger (like a growling dog), while others predict rewards (like the smell of freshly baked cookies). This ability to flexibly adjust our behavior - to avoid harm or to seek out pleasure - is essential for survival. However, when a child grows up in an environment marked by chronic stress or deprivation, these learning systems can become recalibrated in ways that may be adaptive in the short term but costly in the long run (McLaughlin et al., 2014; Oltean et al., 2023). For instance, constantly expecting a threat might make sense in a violent home but may lead to excessive vigilance or anxiety in safe settings later on.

Importantly, the impact of adversity is not limited to threat processing. Reward learning - the ability to detect, anticipate, and respond to positive outcomes - can also be profoundly affected. Children exposed to ACEs may show reduced sensitivity to rewarding feedback, slower learning from positive outcomes, or diminished anticipation of pleasurable events (Gerin et al., 2017; Oltean et al., 2023). Imagine a child in a neglectful environment where praise, warmth, or encouragement are rare - over time, the brain may adapt by dampening its responsiveness to rewards, a pattern that can undermine motivation, social connection, and emotional well-being later in life. This has major implications, not only for understanding mood disorders like depression but also for shaping targeted interventions that aim to rebuild positive motivational systems.

While early research often lumped adversity into a single risk score (McEwen, 2003) or focused on specific events like sexual abuse or neglect, newer models - such as the dimensional model of adversity and psychopathology (DMAP) - highlight that different kinds of adversity, like threat versus deprivation, likely shape different neural and behavioral pathways (Sheridan and McLaughlin, 2014; Ellis et al., 2022). This perspective underscores the importance of examining both how children learn to avoid punishment and how they learn to pursue rewards, as both processes are crucial for adaptive functioning.

Bringing together insights from the largely separate fields of threat and reward learning is crucial for building a more complete understanding of how childhood adversity shapes associative learning and, ultimately, mental health outcomes. This integrated perspective may help refine our understanding of how early adversity relates to psychopathology and could inform future directions for prevention and intervention research. Moreover, highlighting key methodological challenges and gaps in the current research may stimulate new directions for future studies, moving the field toward more precise and individualized models of risk and resilience.

3.2 Methods and Materials

The systematic review was carried out following the PRISMA framework (Moher et al., 2015; Page et al., 2021). The review included studies published up to December 2022 that examined tasks involving either threat or reward learning (both instructed and uninstructed) and explored their connection with ACEs. Search terms in the threat learning category included expressions like 'fear or threat conditioning,' 'aversive anticipation,' and 'threat of shock,' while the reward learning category included terms such as 'reward or reinforcement learning' and 'anticipation of reward.' To capture ACEs-related research, keywords like 'adversity,' 'maltreatment,' 'abuse,' 'neglect,' 'stress,' 'trauma,' 'deprivation,' 'institutionalization,' 'orphanage,' 'adoption,' 'harassment,' 'bullying,' 'household violence,' 'domestic violence,' 'poverty,' 'low socioeconomic status (SES),' 'food insecurity,' and 'adverse childhood experiences' were combined with terms referring to young populations ('children,' 'childhood,' 'early,' 'youth,' and 'adolescents'). Papers were excluded if they were reviews, conference abstracts, conducted with non-human subjects, lacked a learning component, or focused broadly on lifetime trauma rather than ACEs-specific outcomes. Threat or reward learning was broadly defined as observable physiological or behavioral changes over time in response to repeated or prolonged cues. The anticipatory responses to rewards, as captured through BOLD fMRI (Wilson et al., 2018), can be conceptually compared to BOLD responses elicited by conditioned stimuli (CS+ vs. CS-) in threat learning contexts, reflecting the anticipation of threat or safety (see Box 1 for details on the paradigm). R (Version 4.2.3; R Development Core Team, 2023) was used for all data analyses, visualizations, and manuscript preparation. The complete dataset and code used to generate and reproduce the manuscript are freely accessible on Zenodo at: `https://doi.org/10.5281/zenodo.11636897`.

3.3 Results

Literature Search and Study Inclusion

A total of 3,127 publications were initially identified. After screening titles, abstracts, and full texts, 81 articles examining the relationship between ACEs and learning processes were included in the analysis - 38 focusing on threat learning and 43 on reward learning. Details on sample characteristics, ACEs types, and experimental methods are described below and illustrated in Figures 11 and 12.

Sample Characteristics

Comparisons were made across several dimensions in threat and reward learning studies. Regarding participant age, threat learning studies included comparable numbers of pediatric samples (children/adolescents) and adults with childhood adversity (Figures 11A, 11B), whereas reward learning studies showed a slight predominance of child and adolescent samples. Across both research fields, most studies recruited healthy individuals or community samples with minimal exclusion criteria, while only a small number involved clinical populations (Figures 11C, 11D). Notably, threat learning samples were often drawn from high-risk settings, such as low-SES neighborhoods or agencies serving families exposed to violence or food insecurity. In terms of ACEs assessment, most studies did not target specific adversity types (Figures 11E, 11F). Threat learning studies predominantly assessed threat-related ACEs, usually through self-report questionnaires (Figure

11G), whereas reward learning studies also employed official records, diagnostic criteria, and custom assessments (Figure 11H). Some reward learning research focused on factors such as parental substance use or neighborhood disadvantage (“nonspecific” category, Figure 11F). Threat learning research more frequently measured subjective experiences, while reward learning studies were more evenly split between subjective and objective adversity measures (Figures 11I, 11J).

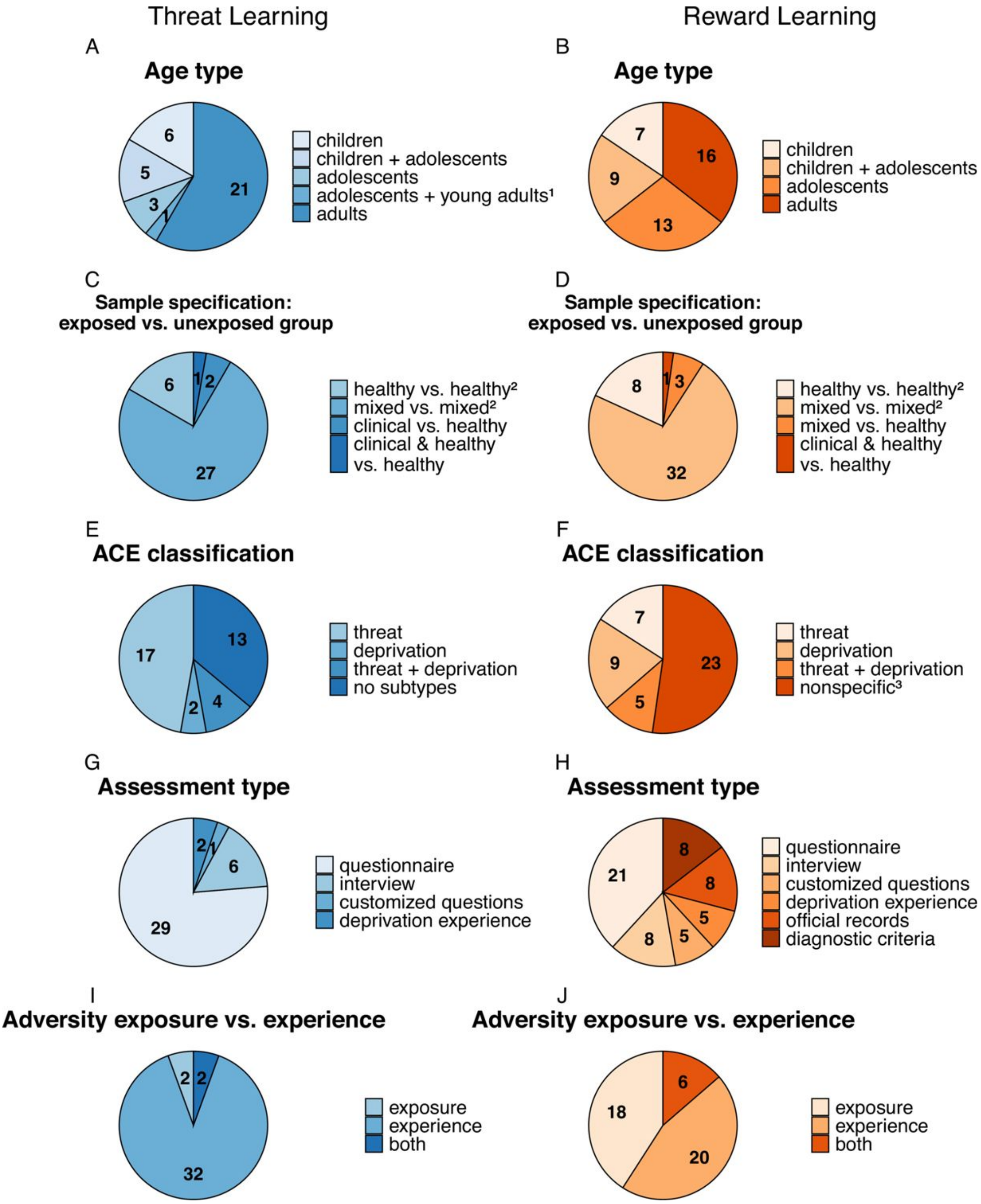


Figure 11: Sample characterization and ACEs assessment instruments in the reviewed studies examining the association between ACEs and learning processes are summarized in Figure 1 (threat learning: n = 38; panels A, C, E, G, I in blue; reward learning: n = 43; panels B, D, F, H, J in orange). The numbers presented indicate the count of studies associated with each characteristic, noting that totals may exceed the number of included studies, as multiple characteristics can apply to a single study. Sample sizes in the individual studies ranged from N = 19 to N = 11,360. 1 Refers to participants aged 2 Includes studies that assess ACEs dimensionally across all participants as well as studies that excluded participants with psychological disorders. 3 Includes studies that assess ACEs that cannot be classified as either threat or deprivation.

Paradigm Characteristics

Most threat learning studies used fear conditioning paradigms (71%), spanning phases such as acquisition, extinction, generalization, and return of fear, while the remaining studies employed other tasks like threat-of-shock or aversive avoidance tasks (Figure 12A). Reward learning studies were methodologically diverse, using 15 distinct paradigms and lacking a clear standard task. The most common was the Monetary Incentive Delay (MID) task (19/43 studies), followed by instrumental reward learning and probabilistic learning (each 3/43), while several other tasks appeared only once (Figure 10B). While tasks like fear conditioning and reinforcement learning are clearly recognized as learning paradigms, the classification of the MID task is more complex. The MID task can also be seen as a learning paradigm because participants adjust their responses based on the size of the reward (Dhingra et al., 2020). Specifically, it leads to gradual changes in sensory processing (Krugliakova et al., 2019), reflecting instrumental or reinforcement learning where particular cues prompt actions that are subsequently rewarded. Primary reinforcers (e.g., aversive stimuli) were predominantly used in threat learning, whereas secondary reinforcers (e.g., monetary rewards) were used in reward learning (Figures 12C, 12D). Measurement approaches also differed: threat learning relied mainly on subjective ratings and psychophysiological measures such as SCR and FPS (labeled “startle” in the graph), whereas reward learning focused on behavioral indicators like reaction time, accuracy, points earned, learning rates, reward prediction error, and fMRI (Figures 12E, 12F).

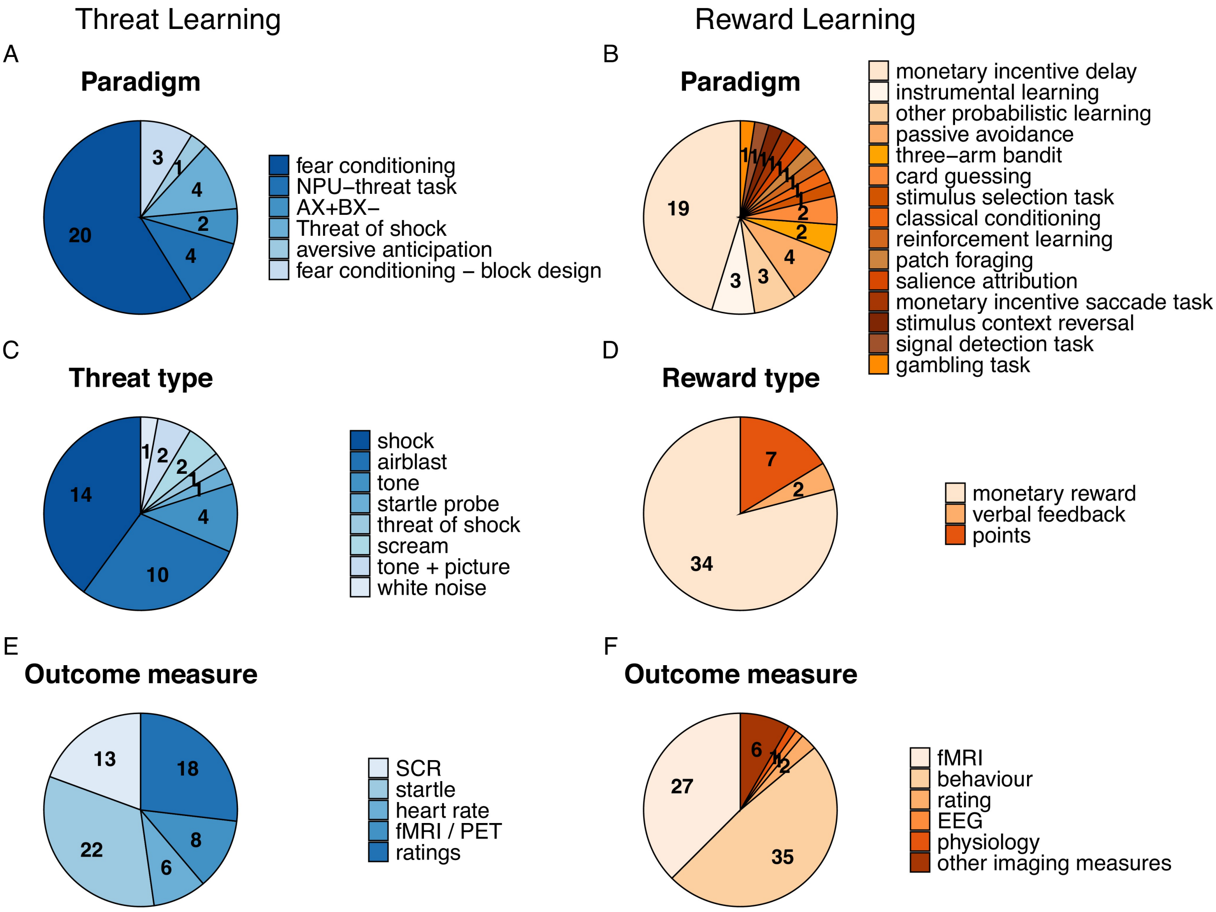


Figure 12: Paradigm characteristics and outcome measures used in the studies included in this review are summarized for threat-related (A, C, E, in blue) and reward-related learning (B, D, F, in orange). The summary includes the type of paradigm (A, B), type of threat or reward employed (C, D), and outcome measures assessed (E, F). The numbers provided indicate the number of studies corresponding to each specification, with the note that totals may exceed the overall number of studies, as multiple specifications can apply to a single study.

Study Quality Evaluation

Study quality was assessed using a tool adapted from Oltean et al. (2023), emphasizing sample characteristics and ACEs assessment, while excluding paradigm specifications due to a lack of objective benchmarks. Many studies (33.3%) had small sample sizes (<30 per group), but half included ≥60 participants, improving result interpretability (see Figure 13). Most samples were at least moderately representative, and psychiatric screening was common (88.9%; Figure 11C,D). In about half the studies, only a few ACEs types were assessed, often using non validated tools or composite scores.

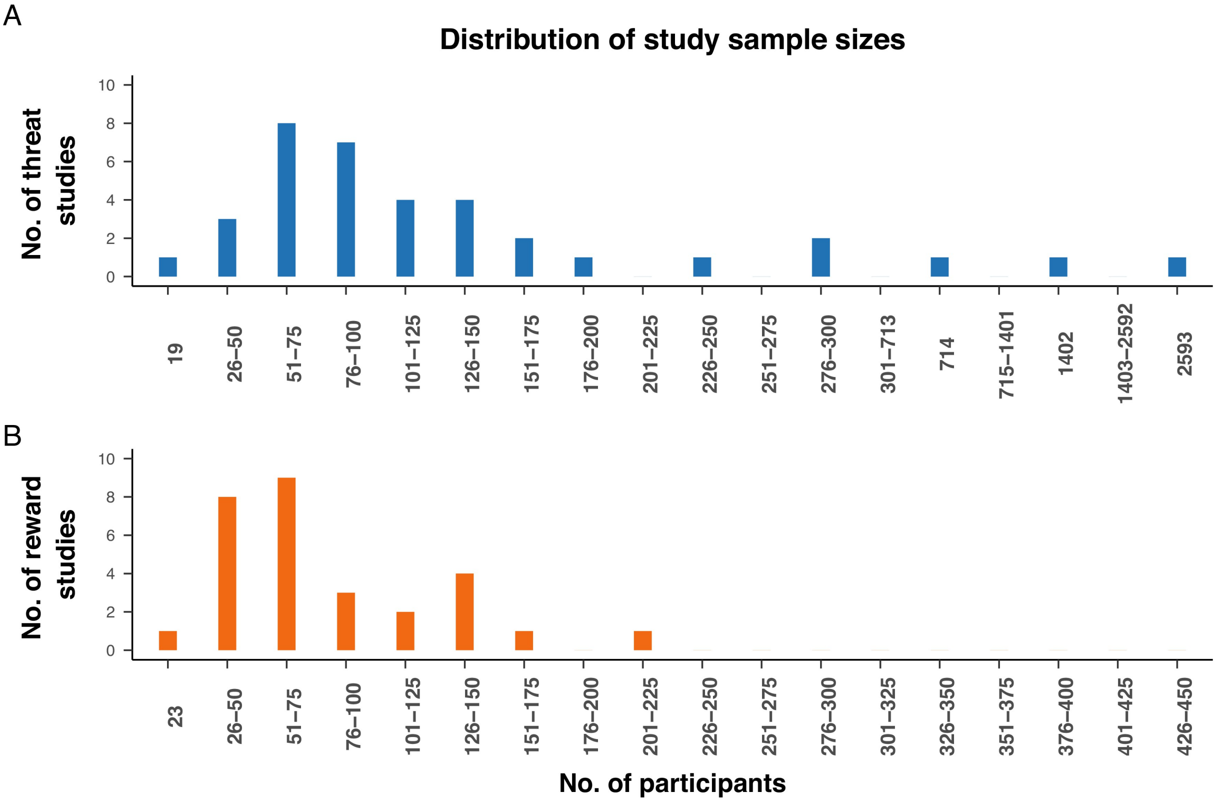


Figure 13: Sample size distribution across studies on ACEs and learning. Panel A shows threat learning studies (n = 38, blue), and panel B shows reward learning studies (n = 43, orange). The x-axis shows participant ranges; the y-axis shows the number of studies per range. Sample sizes ranged from N = 19 to over 2,500.

Associations Between Exposure to ACEs and Threat-Related Learning

The results are organized according to the main phases of a classical fear conditioning paradigm.

Acquisition Phase. Across 21 studies examining threat-related learning, a consistent pattern emerged showing reduced discrimination between cues signaling threat (CS+) and safety (CS−) among individuals with a history of ACEs. This reduction was primarily due to diminished responses to threat cues, as observed in psychophysiological measures such as SCR (Harnett et al., 2019; Klingelhöfer-Jens et al., 2023; Kuehl et al., 2020; Machlin et al., 2019; McLaughlin et al., 2016), FPS (Lis et al., 2020; Stout et al., 2021; Thome et al., 2018), and self-reported fear ratings (Qiu et al., 2023; see Figure 2E for outcome measures across studies). These findings were identified both in adult samples retrospectively reporting ACEs (6 of 10 studies) and in pediatric samples (3 of 5 studies).

However, three studies reported the opposite pattern, with enhanced discrimination between threat and safety cues in ACEs-exposed individuals, as shown in SCR (Marusak et al., 2021) and FPS (Zoladz et al., 2022), and in females only (Morrison et al., 2022).

Interpretation of these findings is complicated by methodological limitations, including unconventional SCR scoring windows (Marusak et al., 2021) and incomplete statistical reporting (Morrison et al., 2022; Zoladz et al., 2022), where crucial interaction tests were not presented. Notably, some studies reporting reduced discrimination also faced methodological issues (Machlin et al., 2019;

Thome et al., 2018), underscoring the importance of consistent methods in this field. Additionally, although less frequently analyzed, ACEs severity was negatively associated with responses to threat cues in some reports (McLaughlin et al., 2016; Qiu et al., 2023), while one study reported no such association (Estrada et al., 2020). Several studies reported null findings across different outcomes, including SCR, FPS, heart rate, valence/arousal ratings, fear ratings, expectancy/contingency, reacquisition, and behavioral measures (Bremner et al., 2005; Estrada et al., 2020; Huskey et al., 2022; Morrison et al., 2022; Scharfenort et al., 2016b; Rowland et al., 2022; Stenson et al., 2021). Interestingly, some evidence suggested developmental differences, such as earlier-than-typical discrimination learning (at 4–5 years) and more mature hippocampal-prefrontal connectivity in children exposed to ACEs (Machlin et al., 2019; Silvers et al., 2016).

Generalization Phase. Reduced discrimination between threat and safety signals extended into the generalization phase in most studies (5 of 7), primarily due to blunted responses to threat cues. For example, blunted SCR (Klingelhöfer-Jens et al., 2023), reduced US expectancy (Qiu et al., 2023), and dampened valence/arousal ratings (Lange et al., 2019) were observed, sometimes alongside elevated safety cue ratings. One study reported enhanced startle to the safety cue in ACEs-xposed females only (Zoladz et al., 2022), though group comparisons were lacking. Importantly, no study found enhanced discrimination during generalization, though several reported null effects across measures such as US expectancy, valence/arousal, risk, fear, and FPS (Lange et al., 2019; Klingelhöfer-Jens et al., 2023; Lis et al., 2020). On a behavioral level, trauma-exposed individuals displayed greater threat uncertainty - shown by longer reaction times - when evaluating ambiguous stimuli, whereas controls showed greatest uncertainty toward cues most similar to the CS+ (Thome et al., 2018). Overall, the pattern across studies points to reduced discrimination, largely driven by dampened responses to threat cues.

Extinction Phase. For extinction learning, 12 studies were reviewed (six without acquisition results). Most reported no ACEs effects on extinction across SCR, FPS, fear ratings, expectancy ratings, heart rate, or behavioral distance (Bremner et al., 2005; Huskey et al., 2022; Kuehl et al., 2020; Marusak et al., 2021; McLaughlin et al., 2016; Scharfenort et al., 2016b; France et al., 2022; Susman et al., 2021). Among the few reporting significant effects, one study found higher US expectancy for the safety cue with greater trauma load and enhanced behavioral distance to the CS+ during extinction recall among children with ACEs (Marusak et al., 2021). Two additional studies observed elevated SCR to the threat cue during extinction in children with ACEs (Jenness et al., 2019; Milojevich et al., 2020). However, inconsistencies were noted, as McLaughlin et al. (2016) and Machlin et al. (2019) reported results from the acquisition phases linked to the same samples analyzed in these extinction studies.

General Reactivity. A subset of studies described heightened general physiological reactivity among ACEs-exposed individuals, seen in elevated FPS, SCR, reduced habituation, and altered risk ratings (Jovanovic et al., 2009, 2020; Kreutzer and Gorka, 2021; Pole et al., 2007; Rowland et al., 2022; Wolitzky-Taylor et al., 2014; Young et al., 2019; Zoladz et al., 2022; Estrada et al., 2020;

Lis et al., 2020; Thome et al., 2018). Kreutzer and Gorka (2021), for instance, observed stronger startle reactions in individuals exposed to interpersonal trauma but blunted responses among those exposed to other trauma types. Jovanovic et al. (2022) found opposite startle-trauma correlations depending on participants' awareness of experimental contingencies. Only one study reported reduced general reactivity (Klingelhöfer-Jens et al., 2023), while others reported null findings across various measures (Young et al., 2018; Huskey et al., 2022; Jovanovic et al., 2022). Neuroimaging Findings. Neuroimaging outcomes, illustrated in Figure 10E, revealed mixed results. Amygdala activation during acquisition showed both blunted CS discrimination (DeCross et al., 2022) and elevated reactivity (Bremner et al., 2005) in ACEs-exposed individuals, alongside null effects (Silvers et al., 2016). Hippocampal responses were likewise inconsistent, with studies reporting both elevated activation (Silvers et al., 2016) and negative ACEs associations (Harnett et al., 2019), as well as null results (DeCross et al., 2022; Scharfenort et al., 2016b). Negative associations between ACEs and prefrontal activation were reported (Harnett et al., 2019). During generalization, no ACEs associations were observed in the amygdala, vmPFC, insula, dACC, hippocampus, or vmPFC (Lange et al., 2019; Morey et al., 2015). During extinction recall, increased dACC and insula activation to the extinguished threat cue was seen among children with ACEs (Marusak et al., 2021).

Associations Between Exposure to ACEs and Reward-Related Learning

The systematic review of studies investigating reward learning revealed a mixture of null findings and studies reporting diminished reward-related performance in individuals exposed to ACEs. Here, the term attenuated reward performance is used broadly to capture various outcome measures across different experimental tasks (see Figure 12B), all reflecting some form of impaired behavior in probabilistic, reward-based reinforcement learning.

Behavioral Findings. Of the 28 studies reporting behavioral data, 14 found evidence for reduced responses to rewarding feedback among individuals with a history of childhood adversity (see Figure 12F). The most commonly assessed indicators of reward learning were task performance measures, including the number of correct responses, points earned, or overall reward accumulation, as well as measures of learning speed such as reaction time or learning rate (Delgado et al., 2022; Dennison et al., 2019; Harms et al., 2018; Patterson et al., 2013; Pechtel and Pizzagalli, 2013; Sheridan et al., 2018; Weiss et al., 2019; White et al., 2022; Wilkinson et al., 2021; Wismer Fries and Pollak, 2017). Studies applying reinforcement learning models identified deficits in reward expectation and the processing of prediction errors in ACEs-exposed groups (Hanson et al., 2017; Letkiewicz et al., 2022). In an exploration-exploitation paradigm, reduced exploration and a lower learning rate were interpreted as reflecting suboptimal strategies for reward maximization in ACEs-xposed individuals (Lloyd et al., 2022). Furthermore, in an incentive saccade task, individuals with ACEs histories showed diminished sensitivity to rewarding feedback and less performance improvement when positive reinforcement was provided (Mueller et al., 2012). One study found that exposed participants rated rewarding cues as less pleasant during a monetary incentive delay

(MID) task (Dillon et al., 2009).

Behavioral Null Findings. Importantly, the same number of studies (n = 14) reported null effects, finding no significant association between ACEs exposure and reward learning performance. The outcome measures used in these null studies were comparable to those in studies reporting significant effects, including response times, success rates, and error counts (Bjork et al., 2008; Boecker-Schlier et al., 2016; Cisler et al., 2019; Dennison et al., 2016; Dillon et al., 2009; Gonzalez et al., 2016; Mehta et al., 2010; Morris et al., 2015; Müller et al., 2015; Smith and Pollak, 2022; Weiland et al., 2013). Measures of reward expectation and prediction error were also included (Cisler et al., 2019). Two studies employed passive avoidance tasks that measured commission and omission errors, showing no effects of ACEs; this may suggest that while active reward learning is affected by ACEs, passive avoidance learning may remain intact (Blair et al., 2022; Gerin et al., 2017).

Neuroimaging Findings. Seventeen studies either partly or entirely used neuroimaging approaches (e.g., fMRI) to assess brain responses during reward anticipation or outcome feedback in individuals with and without ACEs exposure. Ten of these studies reported reduced neural activation during reward anticipation following ACEs exposure, both in broadly distributed networks (Birn et al., 2017; Casement et al., 2014; Dillon et al., 2009; Mehta et al., 2010; Morelli et al., 2021) and in core reward-processing regions, including the ventral striatum and insula (Boecker-Schlier et al., 2016; Gerin et al., 2017; Martz et al., 2022; Mullins et al., 2020; Yau et al., 2012).

In contrast, six studies found evidence of heightened activation during reward anticipation in ACEs-exposed individuals, involving regions such as the thalamus, midbrain, insula, ventral striatum, inferior and medial frontal gyrus, and dorsolateral prefrontal cortex (Casement et al., 2014; DelDonno et al., 2019; Gonzalez et al., 2016; Hendrikse et al., 2022; Kwarteng et al., 2021; Romens et al., 2015).

Three additional studies reported enhanced brain responses during loss feedback or when prediction errors occurred, including regions like the inferior frontal gyrus, cingulate gyrus, superior temporal gyrus, prefrontal cortex, thalamus, and putamen (Birn et al., 2017; Gerin et al., 2017; Yang et al., 2021). Notably, Eckstrand et al. (2019) reported a positive linear relationship between the number of traumatic events and activation in the ventral anterior cingulate cortex (ACC).

Finally, four studies found no differences between ACEs-exposed individuals and controls during reward anticipation (Bjork et al., 2008; Müller et al., 2015; Weiland et al., 2013) or reward delivery (Boecker-Schlier et al., 2016).

Summary of Results

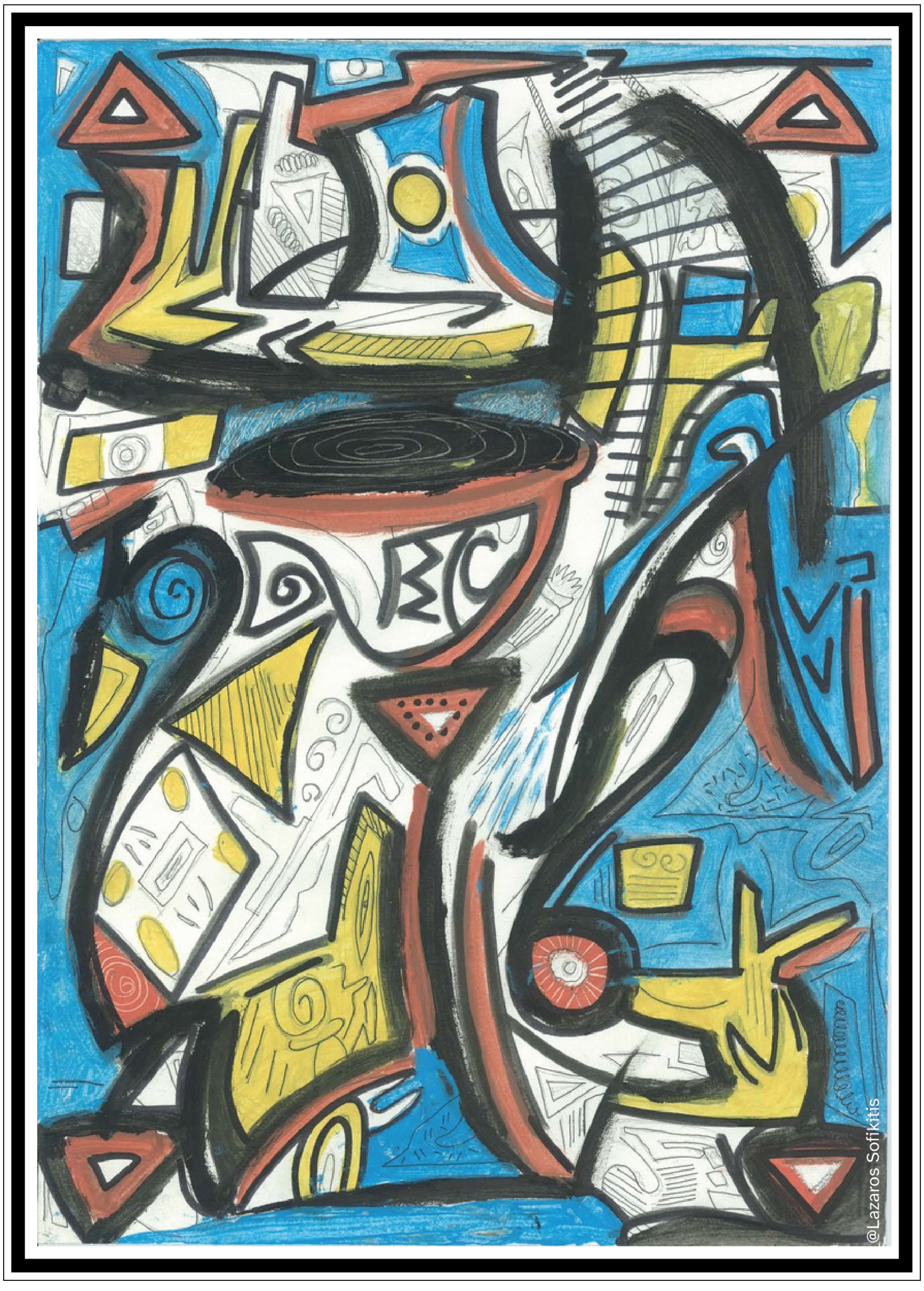
Threat Learning. Across the 21 studies that examined fear acquisition, a consistent pattern of altered learning responses was observed in individuals with a history of ACEs. Specifically, nine studies reported reduced physiological or behavioral responses to threat-related cues, indicating attenuated threat sensitivity during the conditioning process. In contrast, three studies described enhanced responsiveness to threat cues, though these findings are difficult to interpret due to significant methodological limitations discussed elsewhere in this review. When examining the generalization of threat learning, seven studies included a dedicated generalization phase, of which five reported reduced discrimination or blunted responses to threat-associated stimuli in ACEs-exposed individuals relative to controls. Given the expected variability across a large body of empirical work (Lakens and Etz, 2017), the observed pattern supports a directional trend: individuals with ACEs tend to show dampened responses to conditioned threat cues during both acquisition and generalization. Overall, the evidence converges on the interpretation that ACEs exposure is linked to a generally reduced capacity to learn from threatening stimuli.

Reward Learning. Findings from the 28 studies investigating reward learning similarly point toward a disruption in adaptive learning mechanisms among individuals exposed to early adversity. Fourteen studies identified significant reductions in reward learning performance, encompassing impairments in outcome valuation, feedback-based learning, and motivational engagement. These impairments were particularly evident in tasks that required participants to learn probabilistic associations or update their behavior based on reward feedback. Notably, this review expands upon earlier meta-analytic work (Oltean et al., 2023) by focusing specifically on reward learning processes and including deprivation-related adversities such as low socioeconomic status or institutional care. The remaining 14 studies yielded null results, reflecting no significant relationship between ACEs and reward learning measures. However, as with threat learning, such variability is expected within large-scale empirical investigations (Lakens and Etz, 2017), and does not preclude the emergence of reliable effects. Indeed, the overall pattern points toward a consistent attenuation of reward learning in ACEs-exposed populations.

At the neural level, findings were more heterogeneous. Among the 17 neuroimaging studies reviewed, ten demonstrated reduced activation in regions typically involved in reward anticipation, including core components of the brain's reward circuitry such as the ventral striatum and insula. In contrast, seven studies reported increased activation in midbrain structures or across broader cortical networks, suggesting that compensatory or context-specific neural mechanisms may be at play. Despite these inconsistencies, the balance of evidence - particularly in behavioral outcomes - supports the conclusion that individuals with a history of ACEs exhibit generally blunted reward-related learning, both behaviorally and in terms of underlying neural engagement.

Chapter 4:

BEYOND THE LABORATORY



Chapter 4

BEYOND THE LABORATORY

Study 3 - Navigating the approach-avoidance matrix. A novel task in a foraging task in virtual reality

The findings presented here are based on original data analyses and have not yet appeared in a peer-reviewed publication.

Kastrinogiannis, A., Ehlers, M. R., Koppold, A., and Lonsdorf, T. B. (Unpublished manuscript). Navigating the approach-avoidance matrix: A novel task in a foraging task in virtual reality.

How do individuals balance threat avoidance and reward pursuit in real time, and how can immersive methods advance our understanding of these motivational conflicts? In this study, we present a novel VR paradigm to examine approach–avoidance behavior, highlighting the potential of ecologically valid, gamified designs to expand research beyond the lab.

4.1 Introduction

AA behaviors are fundamental mechanisms that help organisms navigate threats and opportunities, maintaining safety while pursuing rewards. As discussed in the general introduction (Chapter 1), avoidance can be adaptive when appropriately deployed, but when excessive or misapplied, it can interfere with daily functioning and contribute to psychopathology, notably anxiety disorders (American Psychiatric Association, 2013; Barlow, 2002).

Traditionally, AA conflicts have been investigated under controlled laboratory conditions. In animal research, avoidance has been studied using both Pavlovian/instrumental paradigms and tasks targeting innate defensive behaviors (see Chapter 1). In human research, adaptations of these paradigms have typically employed discrete and often binary measures (e.g. button presses or reaction time tasks) to capture avoidance or approach behaviors in response to learned threat cues (Lovibond et al., 2009; Cornwell et al., 2013; Solzbacher et al., 2022; Krypotos et al., 2014).

While these approaches have advanced our understanding of AA behavior, they frequently fail to capture the continuous and dynamic nature of such processes and often lack alignment with naturally occurring behaviors seen outside the laboratory (Pittig, 2018; Krieglmeyer & Deutsch, 2010).

A major limitation of these traditional paradigms, as noted earlier in the thesis, is their reduced authenticity (see Chapter 1.3). Experimental settings typically isolate participants from real-world contexts, constraining movement, perspective, and interaction. Recent technological advances, including virtual, augmented, and mixed reality, have offered promising new avenues to overcome these limitations by providing immersive, interactive environments that allow for the continuous capture of naturalistic behavior (Glotzbach et al., 2012; Grillon et al., 2006; Biedermann et al., 2017; Gromer et al., 2021). Notably, virtual reality (VR) methods have enabled the successful translation of classic animal paradigms such as the Elevated Plus Maze (EPM) and the Open Field Test (OFT) into human research, permitting the study of fear, anxiety, and AA conflicts under more realistic conditions (Biedermann et al., 2017, 2022; Gromer et al., 2021; Wilhelm et al., 2005).

Building on these methodological developments, this chapter will discuss a study using a gamified VR task which was introduced to integrate continuous appetitive and aversive elements to simulate real-life decision-making under conflicting motivational demands. Specifically, the task was designed to capture how participants balance reward pursuit and risk avoidance across virtual environments with varying levels of threat and reward. In contrast to binary tasks, the current design enables the assessment of behavioral nuances such as exposure duration, movement trajectories, and transition latencies, providing a richer understanding of AA behavior in ecologically meaningful settings.

Additionally, the study also draws on individual differences frameworks, particularly reinforcement sensitivity theory (RST; Gray, 1970, 1982; Gray & McNaughton, 2003), which posits that motivational behavior is modulated by trait-level sensitivities to reward and punishment. Measures of Behavioral Activation System (BAS) and Behavioral Inhibition System (BIS) traits (Carver & White, 1994) are used to examine how these dispositional factors influence responses to varying motivational contexts within the task.

Although not the central focus and part of the respective manuscript, for the purpose of the current thesis, exploratory analyses also examine whether histories of ACEs may modulate AA patterns, extending prior findings on adversity's impact on threat and reward learning (see Chapters 2 and 3) into a novel, naturalistic behavioral domain.

In sum, this chapter addresses four key objectives:

(1) to determine whether immersive, continuous, and ecologically valid paradigms could effectively capture the dynamic interplay between approach and avoidance motivations.

Behavioral Predictions. To examine this, we applied behavioral measures inspired by methodologies from animal research, adapted for a virtual environment. These include tracking participants' movement trajectories, duration spent in different simulated settings, and latency in transitioning between environments. Each environment was defined by unique combinations of potential rewards and risks (i.e., varying levels of shock threat), detailed further in the Methods section. Participants were expected to show distinct behavioral patterns across these environments. Specifically, longer durations and slower transitions were predicted in safer, low-threat contexts, reflecting a tendency to prioritize safety over potential rewards. Conversely, high-threat, high-reward environments were expected to be avoided or approached more cautiously, with transitions following a gradient aligned with perceived safety.

Motivational Assessment. To verify that participants' choices were guided by internal motivations rather than random behavior, a post-task questionnaire was administered. It was predicted that individuals who endorsed "maximizing survival" as a primary motive would spend more time in high-isk, high-reward environments, indicating strategic engagement despite potential punishment. These individuals were also expected to exhibit slower transitions out of threatening contexts, consistent with deliberate decision-making rather than impulsive avoidance.

(2) To investigate whether avoidance tendencies in threatening contexts change over time - particularly whether initial avoidance gives way to increased approach behaviors. It was hypothesized that, with repeated exposure, participants would habituate to high-threat environments. As familiarity increased, the perceived value of potential rewards was expected to outweigh the initial aversion to threat, resulting in greater engagement with riskier contexts. In the post-task phase, compared to the pre-task baseline, this shift was anticipated to be reflected in longer exposure durations to high-threat environments. Skin conductance levels were also recorded to supplement behavioral observations by indexing arousal and engagement.

(3) to explore the influence of individual differences on AA behavior.

Impact of behavioral activation and inhibition. It was hypothesized that higher BAS-BD and BAS-Reward Responsiveness (RR) scores would be associated with increased time spent in high-reward, high-risk contexts, reflecting a stronger orientation toward appetitive outcomes. Conversely, elevated BIS scores were expected to predict a preference for low-risk, low-reward environments, consistent with a heightened sensitivity to threat. No specific prediction was made regarding the BAS-FUN Seeking subscale.

Impact of early adversity exposure. Early adversity was assessed with the German adaptation of the CTQ (see Chapter 2 for details). The CTQ captures adverse childhood experiences across five domains - emotional, physical, and sexual abuse, as well as emotional and physical neglect - using 28 items rated on a 5-point Likert scale. Participants who scored above the established cut-off for moderate to severe exposure on at least one subscale were classified as exposed. The CTQ has been shown to possess strong psychometric quality, including high internal consistency, reliability, and validity across several dimensions (Saini et al., 2019).

4.2 Methods and Materials

Subjects

This study was part of a broader research project that included a set of questionnaires and three experimental tasks conducted over two consecutive days. Among these tasks were a freezing-elated exercise and a fear conditioning procedure performed inside an MRI scanner. The first day focused on the acquisition phase, followed by the extinction phase on the second day. **Main task.** A total of 277 participants were recruited via online advertisements. However, 16 individuals were excluded from the analysis due to having insufficient usable data (defined as completing fewer than 84% of all trials). Additionally, 7 participants had to discontinue the experiment early due to motion sickness and were also excluded. A further 15 participants were omitted because they did not provide consent for their data to be shared publicly. After these exclusions, the final sample comprised 242 participants (145 women, 94 men, and 1 non-binary individual). The average age was 25.60 years for women (SD = 5.24), 27.74 years for men (SD = 5.39), and 26.0 years for the non-binary participant.

For the analyses reported below, participants were grouped according to whether they scored at or above the moderate-to-severe cutoff on at least one CTQ subscale (see previous section for cutoffs; similar to Study 1). In this context, participants were categorized as CM− (no exposure) or CM+ (exposed to at least one form of maltreatment as defined by the CTQ thresholds). In total, the data of 221 participants (136 CM−, 85 CM+) were included for whom questionnaire data were available. Of these, 130 identified as female, 86 as male, and 2 as non-binary/other. The mean age was 25.9 years (SD = 5.48) in the CM− group and 26.1 years (SD = 5.86) in the CM+ group, with no significant difference in age between groups (t(99) = 0.06, p = .96). Likewise, gender distributions did not differ significantly between groups ($\chi^2(6) = 9.29$, p = .16). For analyses relating ACEs to pre- and post-exploration data, a reduced sample of 192 participants was used, as not all participants had sufficient or balanced data across exploration phases.

All individuals were screened to ensure compliance with MRI participation guidelines and were not on any related medication. Participation involved a two-day commitment, and each participant received a total compensation of 80 euros. The research followed the ethical standards outlined in the Declaration of Helsinki and received approval from the Ethical Review Board of the General Medical Council in Hamburg (PV5808). **Pre and Post Exploration.** For the analysis of the exploration phase, data from 213 participants were retained. Exclusions were applied for several reasons: 22 individuals were excluded for insufficient exploration time - defined as less than 120 seconds combined across the pre- and post-exploration phases - rendering their data unreliable for average-ased analyses. An additional 21 participants completed only one of the two phases, 2 were excluded due to missing files, and 13 (also excluded from the main task analysis) lacked documented consent to use their data. A comparative overview of exclusion reasons across the main task and exploration phase is provided in Figure 14.

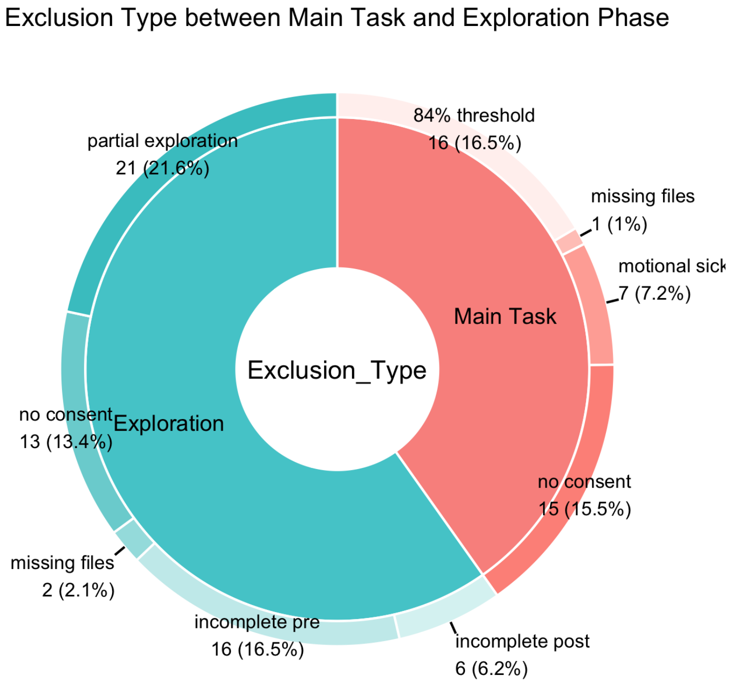


Figure 14: Participant exclusions across experimental phases and types of exclusion. Participants excluded from the main task and exploration phase, categorized by exclusion reason. Inner segments represent the dataset (Main Task vs. Exploration), while outer segments break down the specific exclusion reasons within each dataset. Percentages and counts reflect the proportion of each exclusion reason relative to its respective dataset.

Technologies and Setup

The immersive virtual reality (VR) experience was delivered using the HTC Vive Pro Eye headset (HTC Corporation, Taoyuan, Taiwan), equipped with dual OLED screens and integrated eye-tracking by SensoMotoric Instruments. Each display had a resolution of 1440×1600 pixels and operated at a refresh rate of 90 Hz with a 3.5-inch diagonal size. Experiments took place at the University Medical Center Hamburg-Eppendorf in a designated 5.2 m by 3.1 m space. Participant movement was tracked using two base stations that projected structured infrared light, enabling precise real-time tracking of the HMD's position and orientation via laser sensors, microelectromechanical systems, a gyroscope, and an accelerometer. The virtual scenarios were designed using Unity3D (version 2019.3.7f1, Unity Technologies, San Francisco, USA) and auditory feedback was rendered through the headset's integrated speakers. All rendering was managed by a high-performance PC running on an Intel Core i7-9700K processor (3.60 GHz), supported by 32 GB RAM and a GeForce RTX 2080 SUPER GPU (8 GB). Several 3D models used in the scenarios were created in Blender (`https://www.blender.org`) and subsequently imported into Unity3D. The experimental programming was implemented in C# within the Unity environment.

Electrodermal Activity Measurement

Skin conductance was recorded using a Biopac Bionomadix wireless system with a sampling rate of 2000 Hz and a gain of 5 µΩ. Data was captured using AcqKnowledge 5.0 software. Event markers indicating experimental phases and collected items were transmitted via Unity-Interface software. Self-adhesive Ag/AgCl electrodes (55 mm) were attached to the palmar surface of the participant's left hand (distal and proximal hypothenar regions) after cleansing the area with warm water (without soap). The collected data were processed using Ledalab (v3.4.9) in MATLAB, following guidelines by Boucsein (2012). The signal was downsampled to 10 Hz, and only raw data were analyzed. Recordings started when the VR headset was first worn and continued through all 24 experimental trials, ending just before the headset was removed. Due to significant motion artifacts, only data from 40 participants were included in the final analysis.

Behavioural Inhibition/Activation (BIS/BAS) Scales

To assess individual differences in reward and punishment sensitivity, participants completed the BIS/BAS self-report questionnaire (Carver & White, 1994), which includes 24 statements rated on a 4-point Likert scale (1 = "very true for me" to 4 = "very false for me"). The BAS portion is divided into three components:

- *Drive (BD):* 4 items assessing persistence in goal pursuit.
- *Fun Seeking (FUN):* 4 items evaluating openness to new rewards.
- *Reward Responsiveness (RR):* 5 items measuring reactions to reward anticipation and receipt.

The BIS (Behavioural Inhibition System) scale includes 7 items related to responses to anticipated punishment. Reported internal consistencies for these subscales include α = .74 for BIS, α = .73 for RR, α = .76 for BD, and α = .66 for FUN, indicating varying levels of reliability (Poythress et al., 2008).

Experimental Procedure

Task Instructions. On arrival, participants reviewed written instructions for a gamified approach-voidance task where their objective was to "survive as many virtual days (trials) as possible." They were informed about the varying reward and punishment mechanics in each context, including energy values, coin types, and chances of receiving an electric shock.

Electrotactile Stimulation. Electrical stimuli consisted of three pulses (50 ms apart, 2 ms duration) administered through a 1 cm platinum pin electrode (Speciality Developments, Bexley, UK) placed on the dorsal hand area between the index and middle fingers. Stimulation was delivered via a DS7A stimulator (Digitimer, Elwyn Garden City, UK) and calibrated to each participant's maximum tolerable discomfort level (mean: 1.34 mA, SD: 1.06 mA). Calibration involved participant-controlled testing via a spacebar press. Synchronization between Unity and the stimulator was managed using a custom-programmed Arduino microcontroller (`https://arduino.cc`).

VR Familiarization. Following stimulation calibration, participants donned the VR headset, which was adjusted for comfort. They were initially placed in a neutral VR space where they received interactive instructions on navigation and item collection. Participants practiced controller usage and completed a short training phase involving free collection of virtual apples. A visual energy bar displayed how energy would be consumed and replenished during the main task. Training lasted between two and five minutes, based on participant proficiency.

Experimental Phases

Free Exploration Phase. Participants began by freely exploring a circular virtual world composed of three different naturalistic environments: a water context, a forest, and a desert (Figure 15). They were allowed two minutes to navigate the environment without any specific goals or tasks, both before and after the main experiment.

Main Task Phase. After the free exploration, participants could ask questions before proceeding to the main trials. The primary task consisted of 24 trials. Each trial ended after one minute or earlier if the participant "failed" to maintain virtual health. Trials were grouped into six blocks of four, with rest periods between blocks where participants could remove the headset. Participants had to collect apples that appeared across different zones to sustain virtual energy (Figure 16). Each collection triggered a new apple spawn at a randomized location within a 30 × 30 unit central area of each context (Unity scale units unspecified). Starting positions varied pseudo-randomly by trial.

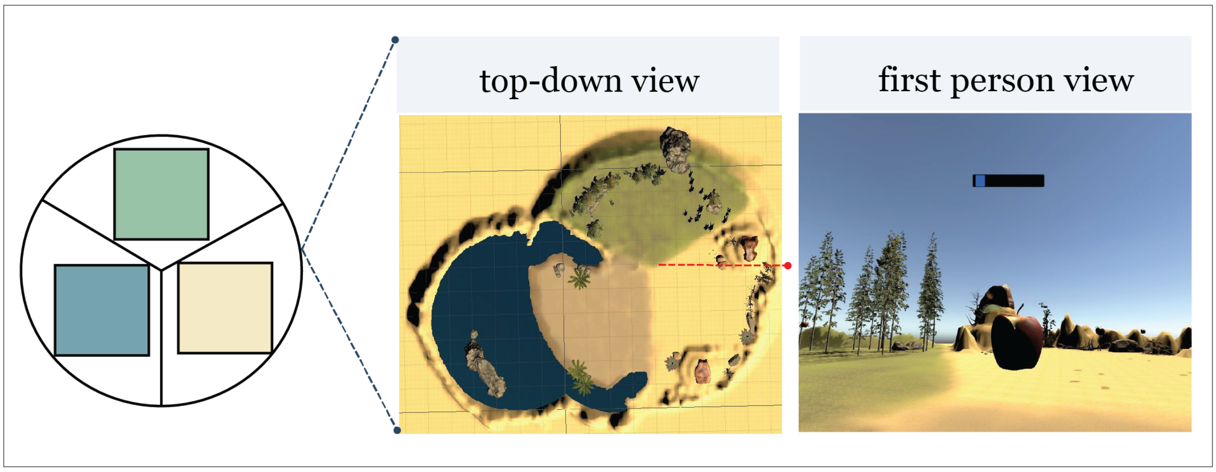


Figure 15: Virtual environment layout and views. Left: schematic of the circular world with three distinct contexts - water (blue), forest (green), and desert (yellow). Middle: top-down view from Unity, with the red dashed line indicating the participant's position and viewing direction. Right: first-person view from the VR headset at the marked position, showing the energy bar and a collectible apple.

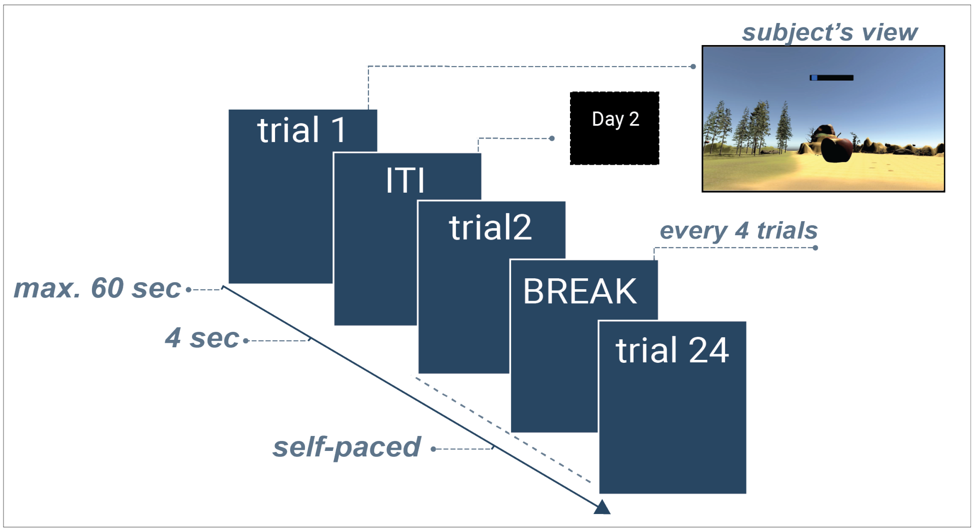
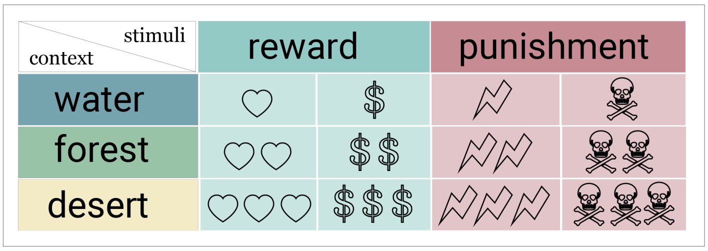


Figure 16: Schematic representation of the experimental task structure. Participants completed 24 trials across one session. Each trial lasted a maximum of 60 seconds and was followed by a 4-second inter-trial interval (ITI). After every block of four trials, participants were offered a self-paced break, during which they could remove the headset and rest. The task resumed with the next trial once participants were ready. The inset shows the participant's in-task view, including the visual representation of their energy level and a virtual apple to be collected.

Reward and Punishment Mechanics To create motivational conflict, each environment was associated with unique combinations of reward and punishment. Rewards were represented by energy points and coin types (bronze, silver, gold) obtained from collecting apples. Punishments consisted of probabilistic electric shocks and context-dependent rates of energy depletion. Three distinct virtual environments were created, each defined by a unique combination of reward magnitude and risk probability:

- → **Water context:** low risk, low reward
- → **Forest context:** moderate risk, moderate reward
- → **Desert context:** high risk, high reward

To enhance immersion, sound effects were used: a pleasant clicking noise played when an unpunished apple was collected, while a thunder sound accompanied apples linked with electrotactile feedback. Audio was delivered via the VR headset. Figure 17 provides a comprehensive breakdown of reward/punishment values per context.



context \ stimuli	reward		punishment	
water	♡	$	ϟ	☠
forest	♡♡	$$	ϟϟ	☠☠
desert	♡♡♡	$$$	ϟϟϟ	☠☠☠

Figure 17: Overview of the reward and punishment contingencies in the three virtual contexts: water, forest, and desert. Reward is represented by heart icons (amount of energy gained per collected item) and dollar signs, which indicate the type of virtual coin contributing to the final score. Punishment is shown with lightning symbols, representing the probability of receiving an electrotactile stimulus, and skull icons, indicating the intensity of energy loss over time. A greater number of each symbol reflects a higher level of the respective outcome.

Statistical Analysis All statistical procedures were carried out using R (version 4.3.3) within RStudio (version 2023.12.1+402). Various R packages were employed for the analyses as detailed below. Due to violations of the assumptions of normality and sphericity associated with traditional repeated-easures ANOVA, linear mixed-effects models were used instead. These models, implemented via the lme4 package, are well-suited for such data as they do not rely on sphericity and are more robust to non-normal distributions. To evaluate the effect of context on the duration spent in each environment, the following mixed-effects model was specified:

```r
model <- lmer(minutes_per_context ~ Context + (1 | Subject))
```

To assess the influence of contextual transitions on transition time, transitions were grouped by direction (e.g., ”water-forest”), and modeled as follows:

```r
model <- lmer(Transition_Time ~ Transition_Type + (1 | Subject))
```

To assess the influence of childhood maltreatment (CM) on exploration time across contexts and phases, the following mixed-effects model was specified:

```r
model <- lmer(minutes_per_context ~ Context * Exploration_Type * CM_Group + (1 |
    Subject))
```

Effect sizes were estimated using partial eta squared (η^2) with the effectsize package (@Ben-Shachar et al., 2020), which quantifies the proportion of variance explained by a given fixed effect relative to the variance remaining (error + effect). Where necessary, post hoc pairwise comparisons were performed using the emmeans package, with Bonferroni correction applied through the pairs() function. For the third hypothesis, Pearson correlation analyses were used to explore the relationship between self-reported strategies (e.g., “tried to get the highest score” or “tried to avoid the electrical stimuli”) and the time spent in each context. The Williams test (via the r.test package) was used to compare correlation strengths, with all p-values exceeding 0.05. To further examine the joint influence of approach and avoidance motivations on time spent across contexts, a linear model including a three-way interaction term (Approach × Avoidance ×

Context) was fitted using the sstats package. Given that the normality assumption was violated for personality questionnaire data (BIS, BAS- BD, BAS-RR), Spearman rank correlations were used for those analyses.

4.3 Results

Time allocation across contexts. The time spent in each context differed significantly between the contexts as indicated by a significant main effect of context type (water, forest, and desert; F(2, 723.00) = 23.06, p < 0.01, $\eta^2 = 0.06$; Figure 18). Participants spent descriptively most time in the water context (M_{water} = 7.96, SE = 0.24), less time in the forest context (M_{forest} = 6.31, SE = 0.24) and least time in the desert context (M_{desert} = 5.75, SE = 0.24). Post hoc analyses indicated that the time spent in the water context was significantly higher than the time spent in the forest and desert contexts (both p's < .001, see Table 3). There was, however, no statistically significant difference between the time spent in the forest compared to the desert context ($t_{\text{forest\_desert}}$(482) = 1.65, p = 0.30).

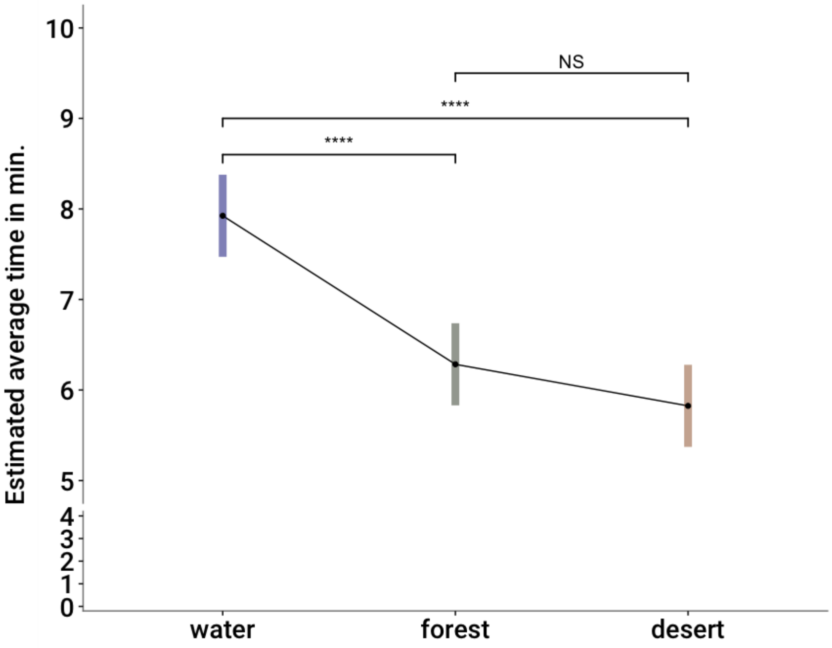


Figure 18: Estimated marginal means and 95% intervals in time spent in each context. Significance lines indicate the results of post hoc comparisons between the means of minutes spent in each context. Statistical comparisons are annotated with significance levels (**** = p < .0001; NS = not significant).

Table 3. Pairwise comparisons of estimated marginal means across contexts (water, forest, desert), including estimates, standard errors, and t-values, extracted from the mixed-effects model and corrected using the Bonferroni method.

contrast	estimate	*SE*	*df*	*t*	*p*
water - forest	1.65	0.34	482.00	4.88	< .001***
water - desert	2.21	0.34	482.00	6.53	< .001***
forest - desert	0.56	0.34	482.00	1.65	.298

Note. * p < .05, ** p < .01, *** p < .001

Transition Patterns Across Contexts. In addition to measuring the time spent within each context, we assessed approach and avoidance behaviors by recording the number of context changes between the different contexts. Numerically, most transitions occurred towards the low reward-low threat context (water) from the other two contexts (forest, desert). Conversely, the numerically fewest transitions were observed from the water context to the high-reward / high-threat context (desert) [Figure 19A]. A Chi Square test for independence revealed that transition frequencies between different contexts (Water, Forest, and Desert) differed significantly, indicating that the starting context significantly influences the transition destination (χ^2 = 2,078.71, df = 4, p < 0.01). In addition, a significant main effect of transition type on the transition time (in seconds) was observed, defined as the time taken to transit from one context to another (F(5, 738.24) = 10.70, p < 0.01, η^2 = 0.07). More specifically, a post hoc analysis using EMMs showed that, starting from the Desert context, the transition time was significantly faster when moving towards the water context compared to transitioning towards the forest context (desert → water vs desert → forest; t(750) = -4.94, p < 0.01; Figure 19B). There was no significant difference in the transition times when participants transitioned from either the water or the forest context to the other contexts (water → desert vs water → forest; t(759) = -2.64, p = 0.09 and forest → desert vs forest → water; t(784) = -0.08, p = 1; Figure 19B).

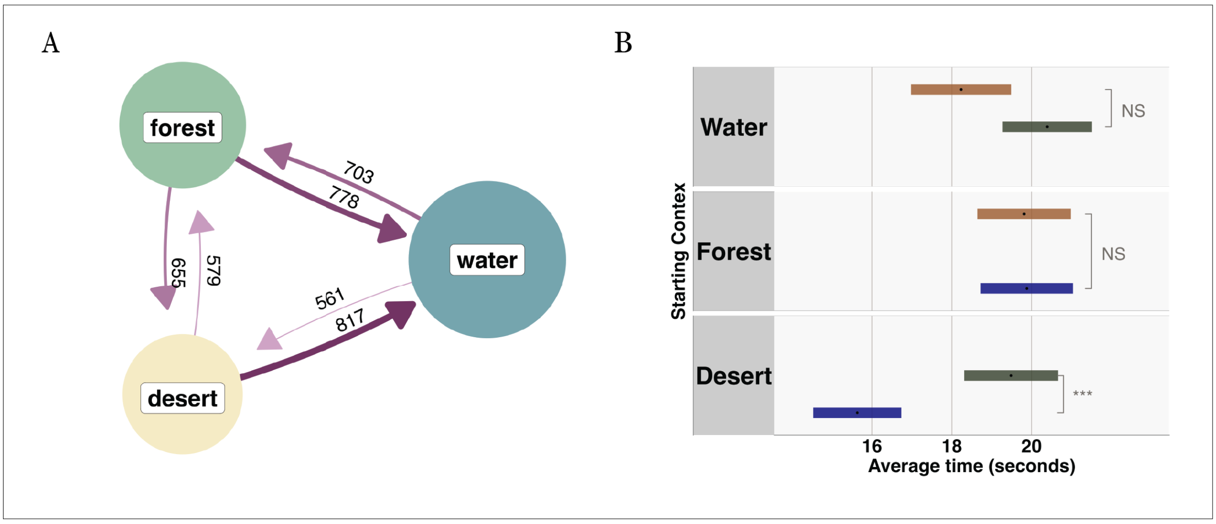


Figure 19: (A) Directed network of observed transitions between contexts. Node size reflects the total number of incoming transitions per context, while edge thickness and color intensity indicate transition frequency (darker and thicker arrows represent more transitions). (B) EMM and 95% confidence intervals for transition times (in seconds), grouped by starting context. Higher values indicate slower transitions. Statistical comparisons are annotated with significance levels (*** = p < .001; NS = not significant).

Analysis of Pre- and Post-Exploration Phases

During pre and post-exploration, the time spent in each context differed significantly [main effect of context [F(2, 1,069.00) = 38.59, p < 0.01, η^2 = 0.07; water > forest > desert] but not between the pre- and post-exploration (no main effect of exploration phase); F(1, 1,069.00) = 1.97, p = 0.16, η^2= 0.00). A significant context x phase interaction was also observed [F(2, 1,069.00) = 6.16, p < 0.01, η^2 = 0.01]. Post-hoc comparisons within the exploration phases showed that during pre-xploration, participants spent significantly more time in the water context compared to both the forest ($t_{\text{water\_forest\_pre}}(901) = 5.54,\ p < 0.01$) and desert context ($t_{\text{water\_desert\_pre}}(913) = 7.57,\ p < 0.01$), while time spent in the forest and desert context did not differ significantly ($t_{\text{forest\_desert\_pre}}(917) = 2.10,\ p = 0.29$). During the post-exploration phase, however, participants only spent significantly more time in the water context compared to the desert context ($t_{\text{water\_desert\_post}}(913) = 7.57,\ p < 0.01$), but not compared to the forest context ($t_{\text{water\_forest\_post}}(908) = 0.59,\ p = 0.99$). In contrast, time spent in the forest and desert context did differ significantly ($t_{\text{forest\_desert\_post}}(900) = 4.29,\ p < 0.01$). Hence, only the time spent in the forest context differed significantly between the pre- and post-xploration phases ($t_{\text{forest\_pre vs forest\_post}}(912) = -3.14,\ p = 0.02$), while this was not the case for the water ($t_{\text{water\_pre vs water\_post}}(907) = 1.78,\ p = 0.47$) or the desert context ($t_{\text{desert\_pre vs desert\_post}}(933) = -1.00,\ p = 0.91$) [Figure 20].

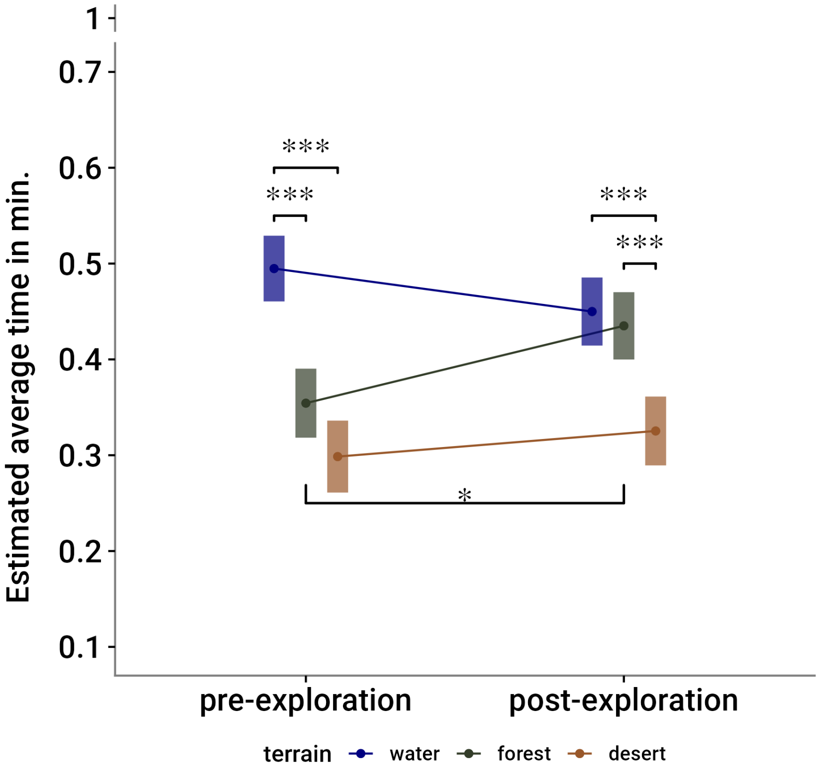


Figure 20: Estimated marginal means and 95% confidence intervals for average time spent (in minutes) within each terrain type (water, forest, desert) across two exploration phases (pre- and post-exploration). Upper brackets indicate between-terrain comparisons within each phase; lower bracket indicates within-terrain comparisons across phases.

Skin Conductance Level

Mixed-effects models revealed a significant main effect of exploration phase, $F(1, 5459.9) = 897.49$, $p < 0.01$, a significant main effect of context, $F(2, 5460) = 38.01$, $p < 0.01$, and a significant exploration phase × context interaction, $F(2, 5461) = 24.49$, $p < 0.01$ (Figure 22). Post-hoc comparisons using z-tests with asymptotic degrees of freedom ($df = \infty$) indicated that during the pre-exploration phase, SCL in the water context was significantly lower than in the forest context ($z = -8.48$, $p < 0.001$), while no difference was observed between water and desert ($z = 2.41$, $p = 0.237$). During the post-exploration phase, SCL in the forest context did not differ from either water ($z = 0.13$, $p = 1.00$) or desert ($z = 2.31$, $p = 0.314$). When comparing pre- and post-exploration phases within each context, SCL increased significantly from pre- to post-exploration in all three contexts: water ($z = -28.98$, $p < 0.001$), forest ($z = -8.76$, $p < 0.001$), and desert ($z = -17.68$, $p < 0.001$).

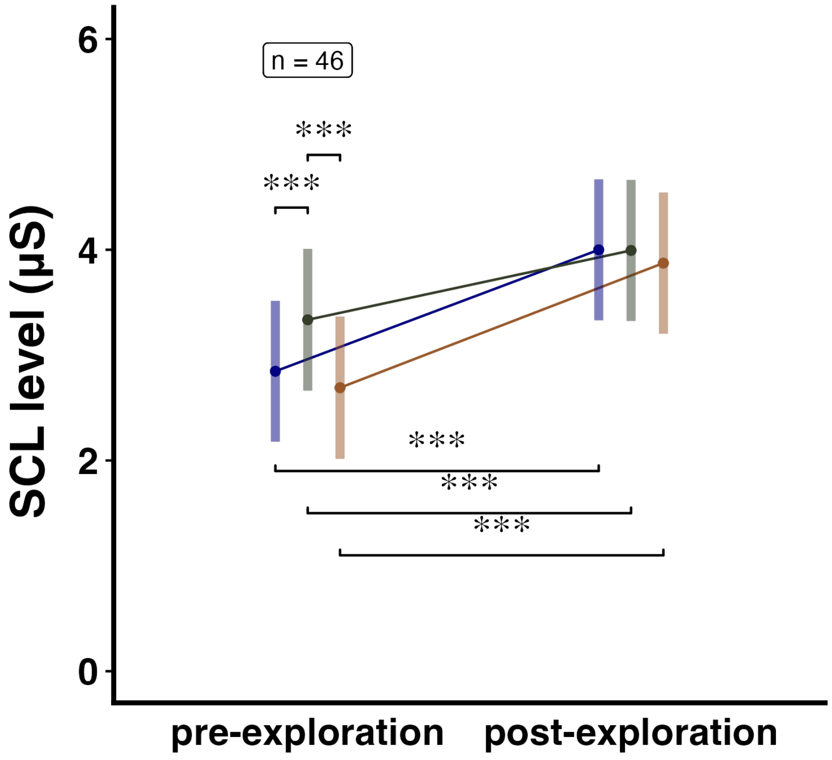


Figure 21: Estimated marginal means and 95% confidence intervals of skin conductance level (SCL; µS) across pre- and post-exploration phases for each context type (water, forest, desert). The upper significance bars represent within-phase comparisons between contexts, while the lower bars represent between-phase comparisons within the same context. Significance levels: (* = p < .05; ** = p < .01; *** = p < .001).

Post-Experimental Ratings

In order to assess the validity of the task further, post-experimental ratings assessed participants' tendencies to either aim for the maximum reward (maximum virtual energy) or avoid the aversive stimuli [Figure 21]. A significant positive correlation was observed between the subjective report of avoidance tendencies (i.e., item "Tried to avoid the electrical stimuli") and the minutes spent in the low reward – low punishment context (water) (r = 0.62, p < 0.001), and a significant negative correlation with minutes spent in the high reward – high punishment context (desert; r = -0.61, p < 0.001).This suggests that participants who reported stronger avoidance tendencies intended to spend more time in the safest context (i.e., water) and less time in the riskiest one (i.e., desert), aligning their preferences with the safety-reward trade-off. Similarly, the reported tendency to gain a high score (i.e., item "I tried to get the highest score") was negatively correlated with the amount of time spent in the low reward water context (r = -0.34, p < 0.001] but significantly positively correlated with the time spent in the high reward desert context r = 0.45, p < 0.001). This indicates that participants who aimed for a higher score chose to spend more time in the context with the highest potential reward (i.e., desert), even though it also had the highest likelihood of being aversive. Participants with stronger avoidance tendencies (i.e., higher ratings on "Tried to avoid the shocks") showed a small but statistically significant negative correlation with time spent in the forest context (r = -0.14, $p < 0.05$). In contrast, the correlation between high approach tendencies and time spent in the forest context was not significant (r = -0.03, p = 0.7).

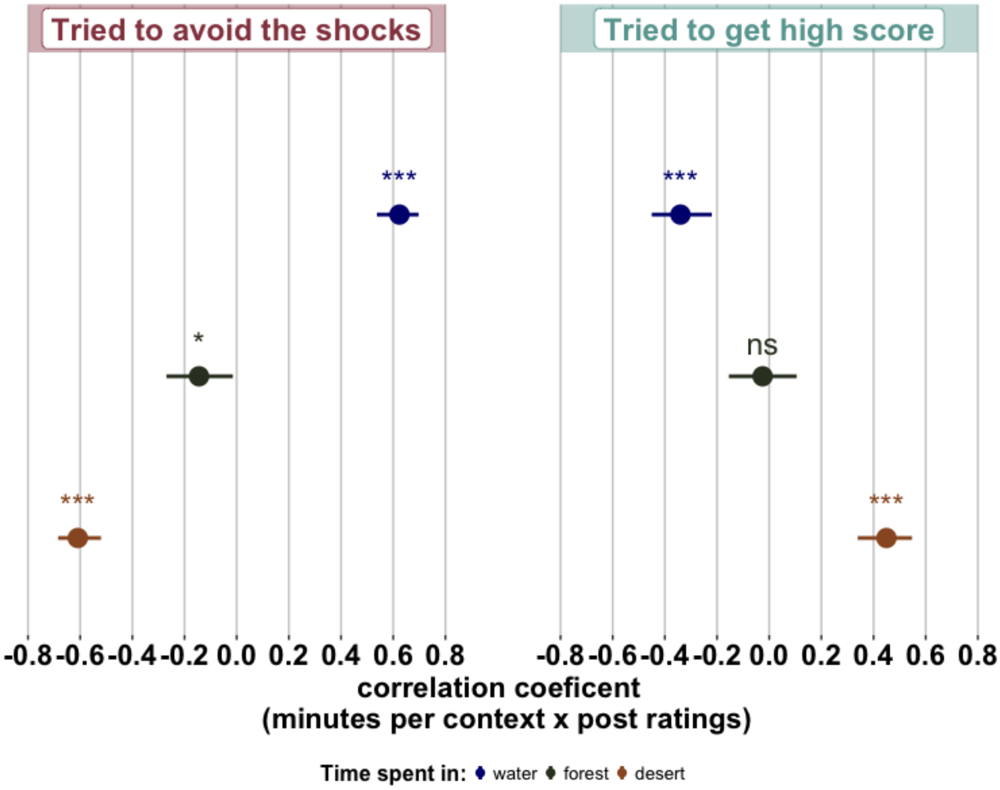


Figure 22: Pearson correlation coefficients showing the association between participants' post-survey ratings of motivational tendencies - avoidance (left panel) and approach (right panel) - and the time spent in each context (water, forest, desert). Error bars represent 95% confidence intervals. Asterisks indicate statistical significance (*** = $p < .001$; ns = not significant).

To examine how motivational tendencies (approach and avoidance ratings) predicted context-elated behavior, we ran a multiple linear regression predicting time spent in each context. The model included main effects and interaction terms for approach rating, avoidance rating, and context (with water as the reference). A significant three-way interaction emerged between approach, avoidance, and the desert context (β = -0.09, SE = 0.03, $p < 0.01$), indicating that the relationship between approach and avoidance ratings and time spent in a context differed in the desert relative to water. In the desert, participants with stronger approach tendencies (e.g., motivated by scoring) spent more time, while those with stronger avoidance tendencies (e.g., motivated to avoid shocks) spent less time — demonstrating a pronounced motivational trade-off in this high-threat/high-reward setting. In contrast, the interaction term for the forest context was not significant (compared to water; β = 0.04, SE = 0.03, p = 0.13), suggesting that motivational influences in forest and water contexts did not significantly differ. Additionally, in the water context (i.e., the reference), higher avoidance significantly predicted more time spent (β = 0.71, SE = 0.13, $p < 0.001$), while approach marginally negatively predicted time spent (β = -0.26, SE = 0.12, $p < 0.05$). In the forest context, only avoidance significantly predicted time spent. More precisely, approach did not significantly predict time spent, though the effect was negative (β = -0.09, SE = 0.07, p = 0.22), while avoidance significantly negatively predicted time spent (β = -0.14, SE = 0.07, p < 0.05). In the desert context, both tendencies were significant: approach significantly positively predicted time spent (β = 0.35, SE = 0.07, p < 0.001), while avoidance significantly negatively predicted time spent (β = -0.69, SE = 0.07, p < 0.001). These findings highlight that motivational dynamics were most pronounced in the desert environment, where reward pursuit and threat avoidance exerted competing influences on behavior.

Relationship Between Approach/Avoidance Tendencies and BIS/BAS Scores

In this sample, the average scores for the (BIS) and BAS were 15.24 (SD = 4.09, range = 7–28) and 24.0 (SD = 5.07, range = 13–37), respectively. These two measures were not significantly correlated [Spearman's ρ = 0.07, p = 0.255]. Contrary to expectations, no significant associations were found between time spent in any of the environmental contexts and the BAS subscales related to BD and RR [all p-values > 0.10]. Interestingly, although no specific prediction was made for the BAS FUN Seeking subscale, a significant negative correlation emerged between this measure and the time participants spent in the desert context (characterized by both high reward and high threat) [Spearman's ρ = −0.19, p = 0.004]. As for the BIS subscale, no meaningful correlations were found with the duration spent in any of the three environments [all p-values > 0.10]. These results are summarized visually in Figure 23.

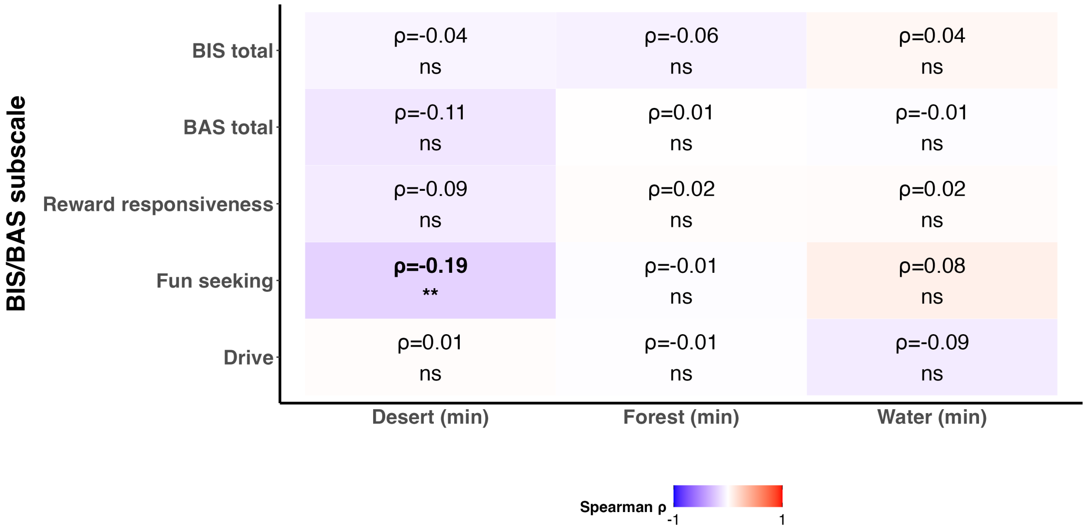


Figure 23: Spearman correlations between BIS/BAS subscales and time spent in each environmental context (water, forest, desert). Tiles are color-coded by correlation coefficient (ρ), with red indicating positive and blue negative associations. Numbers inside the tiles represent correlation coefficients (ρ), with stars denoting statistical significance: (* = p < .05; ** = p < .01; *** = p < .001; ns = no significance).

Effects of Exposure to ACEs on Time Spent per Context, Transition Time, and Exploration Time

The effect of childhood maltreatment (CM) on time spent per context (minutes per terrain) was first examined. The mixed model revealed a strong main effect of Terrain (F(2, 657) = 14.06, p < .001), indicating differences in exploration time across contexts. By contrast, there was no main effect of CM exposure (F(1, 657) = 0.10, p = .755) and no Terrain × CM interaction (F(2, 657) = 0.21, p = .812), suggesting that CM did not modulate overall time allocation across environments.

Analysis of transition times between contexts showed robust main effects of Transition Type (F(5, 2327.07) = 24.46, p < .001) and, critically, a significant Transition Type × CM interaction (F(5, 2316.99) = 4.81, p < .001), while the main effect of CM exposure alone was not significant (F(1, 199.64) = 0.77, p = .383). Follow-up pairwise comparisons revealed that this interaction was primarily driven by the Water → Desert transition: CM+ participants required significantly longer time than CM− participants to move from Water → Desert (t(681.08) = 3.73, p < .001), whereas no other between-group contrasts reached significance.

To further examine within-group patterns, we tested whether participants prioritized specific destinations depending on the starting context. As shown in Figure 24, CM− participants transitioned more quickly from Water → Desert than from Water → Forest (t(2348.60) = −7.03, p < .001). In contrast, CM+ participants showed no such difference (Water → Desert vs. Water → Forest: t(2302.15) = −0.24, p = 1.00). No other within-group contrasts indicated reliable group-specific preferences.

Overall, groups did not differ in their average transition times across contexts. However, CM− participants were faster than CM+ participants when moving from Water → Desert vs Water → Forest, while no group differences emerged for other transitions.

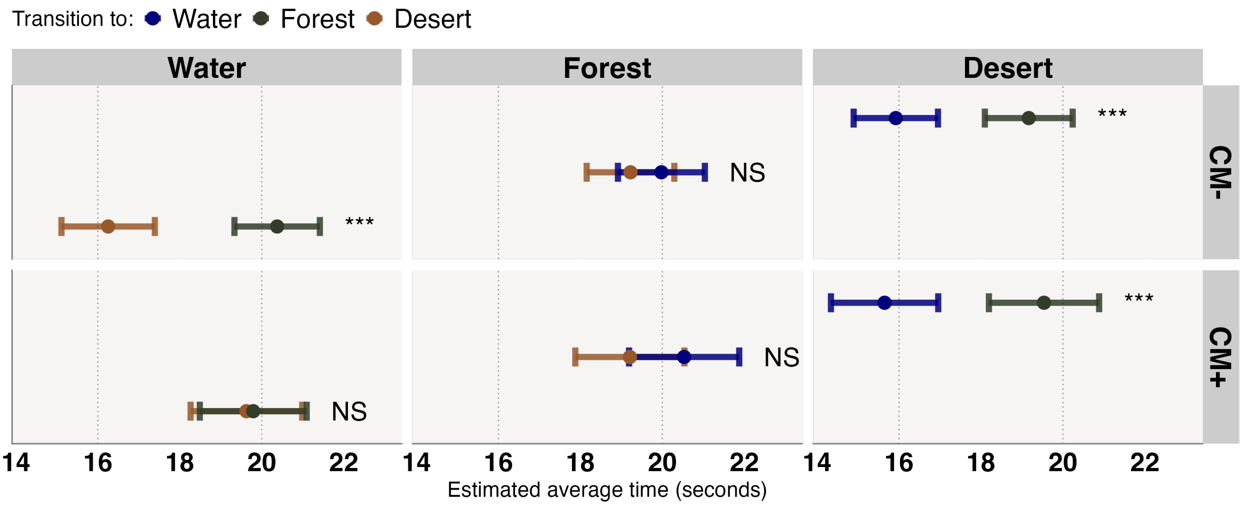


Figure 24: EMM and 95% confidence intervals for transition times (in seconds), grouped by starting context and CM status. Panels separate participants not exposed to childhood maltreatment (CM−) and those exposed to childhood maltreatment (CM+). Colors indicate the destination context (Water = navy, Forest = brown, Desert = ochre). Higher values reflect slower transitions. Statistical comparisons within each CM group are annotated with significance levels (*** = p < .001; n.s. = not significant).

Next, the effect of CM on time spent per context (in minutes) during pre- and post-exploration was examined. There was a significant main effect of context, (F(2, 2719.06) = 96.38, p < .001,η^2 = .07), indicating that participants spent different amounts of time in water, forest, and desert contexts overall. By contrast, there were no main effects of exploration phase (F(1, 2772.15) = 2.52, p =

.113, η^2 = .001), or CM group (F(1, 138.87) = 0.41, p = .525, η^2 = .003). A significant terrain x phase interaction emerged (F(2, 2728.44) = 22.75, p < .001, η^2 = .02) showing that pre–post changes differed across terrains. Additionally, there was a significant phase x group interaction (F(1, 2772.15) = 5.21, p = .023, partial η^2 = .002), suggesting that changes from pre- to post-exploration differed between CM+ and CM− participants. The three-way interaction (terrain x phase x group) did not reach significance (F(2, 2728.44) = 2.38, p = .093, η^2 = .002), indicating that these differences were not consistent across all terrains. Post hoc contrasts clarified the source of the phase × group interaction. Namely, for the CM+ group, exploration time in the water context decreased significantly from pre- to post-exploration (t(2767.95) = 4.40, p < .001). By contrast, the CM− group did not show a significant pre–post change in the water context (t(2784.63) = 1.02, p = .309). In the desert context, the opposite pattern was observed: the CM− group increased their exploration time significantly from pre- to post-exploration (t(2829.82) = −2.17, p = .030), whereas the CM+ group showed no significant change (t(2781.13) = 0.12, p = .906). Both groups showed significant reductions in forest exploration time across phases (CM−: t(2782.00) = −4.22, p < .001; CM+: t(2781.50) = −3.58, p < .001). A visualization can be seen in Figure 25.

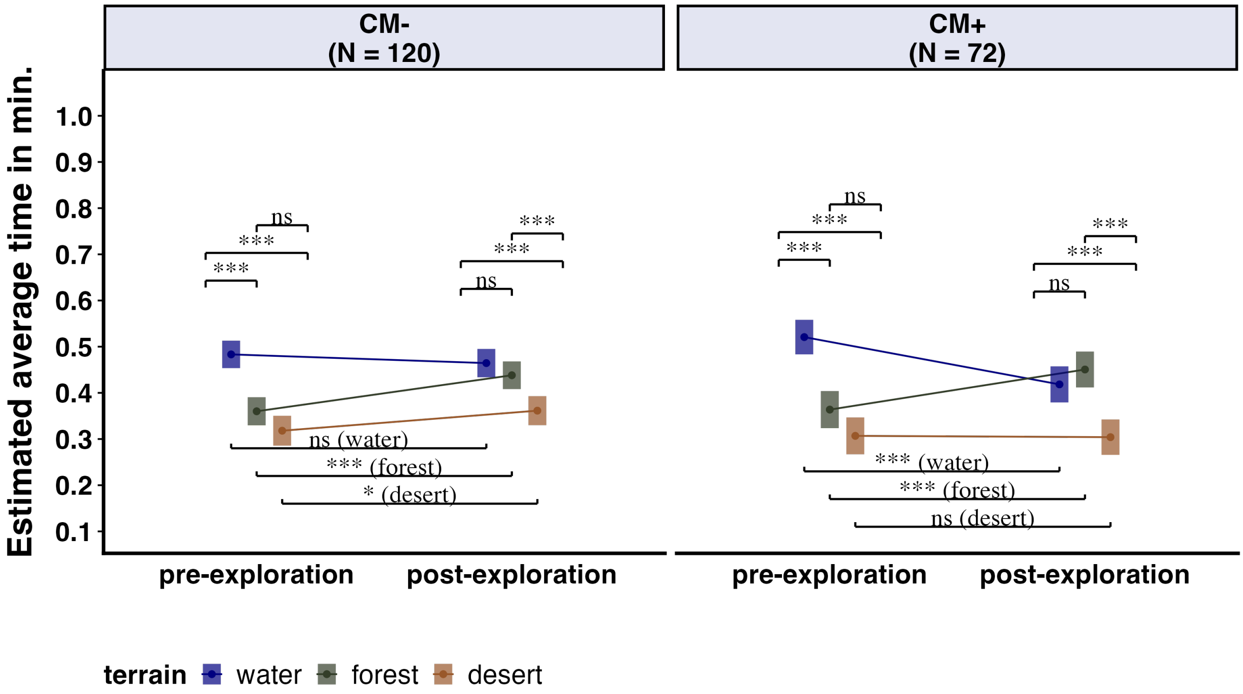


Figure 25: Estimated marginal means and 95% confidence intervals of exploration time (minutes per context) across pre- and post-exploration phases for each context type (water, forest, desert), shown separately for CM− and CM+ groups. The upper significance bars represent within-phase comparisons between contexts, while the lower bars represent between-phase comparisons within the same context. Significance levels: (* = p < .05; ** = p < .01; *** = p < .001; ns = not significant) .

Chapter 5:

DISCUSSION

Chapter 5

Discussion

This section synthesizes the dissertation's findings across studies with two aims: first, to situate the results of each study in their immediate methodological and theoretical context (Section 5.1), and second, to integrate these strands into a broader account of how adversity becomes embedded in physiological and behavioral systems and how this knowledge can guide future work (Section 5.2).

5.1 Cross-Study Discussion of Findings and Limitations

At the core of survival lies the capacity to flexibly adapt to challenges in the environment. Organisms must detect and interpret signals of potential danger or opportunity, regulate physiological arousal, and choose behaviors that minimize harm while maximizing reward. These processes, which range from split-second defensive reactions to gradual patterns of learning and motivation, are generally protective. Yet, when they become dysregulated, they can contribute to maladaptive outcomes such as heightened vigilance, avoidance, or diminished sensitivity to reward - patterns closely linked to the emergence of stress-related and affective disorders (Barlow, 2002; Phelps et al., 2014).

Against this background, understanding how adverse experiences influence such mechanisms of emotional processing is crucial. Childhood and adolescence represent periods of particular sensitivity, when neural and behavioral systems are highly responsive to environmental input. ACEss such as threat and deprivation may therefore leave lasting imprints on physiological reactivity, learning processes, and motivated behavior (McLaughlin et al., 2014; Teicher Samson, 2016). Stressors experienced closer adulthood, in turn, may interact with or alter these pathways in distinct ways, either compounding earlier vulnerabilities or shaping adaptive recalibrations (Lange et al., 2019).

This dissertation examined these questions across three complementary studies: (1) a large-scale psychophysiological investigation of physiological reactivity following childhood and recent adversity, (2) a systematic review integrating evidence on the association between ACEss and threat as well as reward learning, and (3) a novel immersive paradigm probing AA behavior under varying threat and reward contingencies. Together, these studies provide converging perspectives on how exposure to adversity becomes embedded in physiological and behavioral systems, while also highlighting how methodological choices - especiall in task design - affect the conclusions we draw.

In the following parts of section 5.1, the results of each study will be discussed in detail, integrated with prior literature, and considered in light of shared and divergent patterns. Particular attention will be given to proximity to adversity (early vs. late), differences between physiological and behavioral outcomes, and the role of methodological advances in shaping responses. Finally, the studies will be synthesized to outline possible mechanistic pathways, the potential moderating role of protective influences, and the importance of refining measurement approaches to advance the field.

5.1.1 When Timing Matters: Divergent Effects of Childhood and Recent Adversity

This study examined how childhood and recent adversity relate to physiological reactivity and affective modulation of startle EMG and SCR in a large sample of 685 mentally healthy participants. As expected, we replicated previous findings (Kuhn et al., 2016) showing that individuals with adversity histories reported higher levels of trait anxiety and depressive symptoms (Mirman et al., 2021; Zhang et al., 2021). We also explored whether adversity subtypes could be distinguished, given theoretical models suggesting differential consequences of threat versus deprivation (McLaughlin et al., 2014), and assessed convergence between two widely used retrospective questionnaires, the CTQ and KERF/MACE.

Across the full sample, we replicated the expected affective modulation patterns, with EMG startle magnitude scaling with stimulus valence and SCRs scaling with stimulus arousal (Hartman et al., 2021; Kuhn et al., 2020; Lang et al., 1990). Based on earlier reports (Lis et al., 2020; McTeague et al., 2010; McTeague Lang, 2012), we anticipated that adversity would attenuate affective modulation of both EMG and SCR, particularly for negative material. Our findings only partially supported this expectation: individuals with a history of childhood maltreatment exhibited reduced SCR modulation compared to non-exposed participants. This effect appeared to be driven by a diminished differentiation between neutral and negative pictures, resulting primarily from heightened SCRs to neutral rather than blunted responses to negative stimuli. Indeed, in both participants with early-life and recent adversity exposure, SCR modulation was essentially absent, with responses across valence categories being comparable. These results echo previous reports of reduced SCR differentiation between safety and danger cues in maltreated children and adolescents (McLaughlin et al., 2016), and align with findings in clinical populations such as patients with anxiety disorders, where reduced startle discrimination between conditioned safety and danger cues has been linked to impaired inhibitory mechanisms (Cooper et al., 2018; Grasser Jovanovic, 2021; Jovanovic et al., 2009, 2010). While those studies focused on discrimination between safety and danger cues, the present findings of Study 1 suggest a conceptually similar difficulty in differentiating between neutral and negative stimuli. Interestingly, exposure to recent adversity revealed a contrasting pattern: it was associated with increased affective modulation of SCRs, largely explained by attenuated responses to neutral stimuli. This finding converges with earlier work by Najström and Jansson (2007), who demonstrated that increased SCRs to masked threatening stimuli predicted stronger emotional reactions to later stressful life events, a phenomenon interpreted as preferential pre-attentive processing that may contribute to anxiety risk. While our paradigm did not involve masked presentation, both results highlight that enhanced SCR responses to non-salient or ambiguous stimuli may signal increased vulnerability to stress. In summary, our results suggest a developmental dissociation in how adversity shapes sympathetic activation: childhood adversity was associated with dampened modulation, whereas recent adversity was linked to enhanced modulation. Related work by Scharfenort et al. (2016) similarly showed that individuals with recent adversity displayed reduced safety-danger discrimination during fear recall and reinstatement, pointing to difficulties in flexibly regulating responses after stress exposure. Taken together, these findings suggest that the timing of adversity may contribute to distinct physiological response patterns, although more systematic evidence is needed before firm conclusions can be drawn.

It should be noted that adversity-by-modulation interactions were not robust when the analysis was restricted to SCR responders, where sample size dropped from 532 to 272. This may reflect reduced statistical power but also raises the possibility that excluding non-responders removes meaningful interindividual variance, as non-responding has itself been linked to systematic factors. For instance, in our sample, non-responders were disproportionately often female and tended to report lower anxiety, lower depression, and more frequent histories of childhood maltreatment, albeit not at statistically significant levels. These patterns are consistent with Susman et al. (2021), who noted an overrepresentation of SCR non-responders among youth exposed to violence and other forms of threat-related adversity. Additionally, Similar concerns have been raised in the fear-onditioning literature, where non-responder exclusions risk removing precisely those individuals whose response patterns may be most informative (Lonsdorf et al., 2019).

Contrary to our preregistered hypothesis (Iffland et al., 2014a; McLaughlin et al., 2015; McTeague Lang, 2012), we did not observe globally blunted physiological responses in adversity-exposed participants. Instead, individuals with recent adversity exhibited higher general SCR reactivity, while childhood adversity had no consistent effect on general SCR or EMG responsiveness. This finding adds to the growing evidence for heightened autonomic reactivity following recent stress exposure across age groups (Giuliano et al., 2018; Cushman et al., 2021; Stout et al., 2021). Supporting this, Susman et al. (2021) found that elevated sympathetic activation (indexed by SCRs during extinction learning) predicted increases in a broad range of psychopathology symptoms across diagnostic categories (“transdiagnostic symptoms”), including internalizing, externalizing, PTSD, and general psychopathology.

By contrast, startle EMG modulation did not differ between exposed and non-exposed individuals, regardless of adversity timing. This stands in contrast to reports of reduced EMG discrimination following childhood adversity in paradigms involving threat of shock or explicit fear conditioning (e.g., Jovanovic et al., 2010; Pole, 2007; Pole et al., 2009; Wolitzky-Taylor et al., 2014). The discrepancy may stem from the relatively mild emotional challenge of passive picture viewing compared to threat-of-shock paradigms (Lissek et al., 2006). Consistent with this interpretation, prior studies have shown that adversity effects on startle EMG emerge primarily under high-threat conditions (Pole, 2007) and are moderated by subjective aversiveness of startle probes (Poli Angrilli, 2015). Similarly, Dackis et al. (2015) reported null effects of childhood maltreatment on startle modulation in an affective picture-viewing task. Thus, our null EMG findings may reflect task-specific sensitivity limits.

Another potential interpretation stems from resilience. According to the “U-shaped” model of stress exposure (Seery et al., 2013), moderate cumulative adversity may actually enhance stress resilience relative to both very low and very high exposure. In line with this, Stenson et al. (2021) reported stronger fear inhibition in children exposed to moderate maternal trauma. In our sample of healthy adults, adversity-exposed participants - recruited specifically without any lifetime psychiatric diagnoses in themselves or their first-degree relatives - may represent a resilient subgroup, showing no startle differences compared to controls. This raises the broader question of whether adversity-linked alterations in psychophysiological responses should be understood as indicators of risk, resilience, or both. On the one hand, blunted modulation resembles patterns observed in clinical populations and may index vulnerability. On the other, the absence of differences in healthy, adversity-exposed individuals could reflect adaptive recalibration. Distinguishing between these possibilities will require longitudinal, multi-level studies that track adversity-exposed individuals across development, combining psychophysiological markers (e.g., SCR, EMG), subjective experience, and clinical outcomes, and comparing healthy versus clinical groups in both controlled and authentic contexts (see Chapter 1.3; Section 5.2).

Our exploratory analyses also indicated that physical maltreatment was associated with reduced SCR reactivity in adulthood, pointing to alterations in general sympathetic reactivity. This finding extends earlier reports of blunted startle responses in physically maltreated boys (Klorman et al., 2003) and diminished SCRs to conditioned threat cues in maltreated youth (McLaughlin et al., 2016). More recently, Machlin et al. (2019) found that threat (but not deprivation) predicted reduced SCR amplitudes to the unconditioned aversive tone in young children, again reflecting blunted general reactivity. In our own data, threat-related adversity was likewise linked to reduced general EMG responding, though only among non-deprived participants. These results are preliminary but highlight the potential utility of distinguishing threat from deprivation (Sheridan McLaughlin, 2014; Teicher et al., 2021). However, recent critiques emphasize that distinctions such as threat versus deprivation are often “fuzzy” in practice, since most children experience overlapping forms of adversity, and both categories tend to involve elements of each other (Smith Pollak, 2021). Moreover, the neurobiological correlates linked to these categories, such as alterations in amygdala, hippocampus, and stress-response systems, show substantial overlap across subtypes. Thus, while our exploratory findings align with the threat–deprivation framework, they should be interpreted cautiously.

Finally, a mojor challenge lies in the measurement regarding the exposure to early adversity. Our comparison of CTQ and KERF/MACE yielded only moderate agreement for categorical exposure classifications and variable agreement across dimensional measures, consistent with prior work (Isele et al., 2014). This underscores the so-called “toothbrush problem” in adversity research (Flake Fried, 2020; Karstoft Armour, 2022): each study uses different measures and cutoffs, hampering cross-study synthesis. As others have argued (Lonsdorf et al., 2022; Simonsohn et al., 2020; Steegen et al., 2016), multiverse-style analyses that explore multiple operationalizations may offer a path forward. Additionally, recent work by Koppold et al. (2024) has systematically examined the item-level overlap and divergence between commonly used adversity questionnaires, underscoring the importance of careful instrument choice for ensuring comparability and cumulative knowledge generation. The present findings indicate that both childhood and recent adversity may alter the modulation of physiological responses, albeit in opposite directions depending on developmental timing. Such altered modulation likely reflects differences in how cues of threat and safety are processed and discriminated, and how motivational salience is assigned. These processes lie at the heart of associative learning, where organisms must flexibly update responses to signals of danger and reward. To place these observations in a broader framework, study 2 synthesizes evidence from the literature on threat and reward learning in the context of childhood adversity.

5.1.2 When Learning Falls Silent: Blunted Threat and Reward Processing after Childhood Adversity

Study 2 synthesized evidence across studies examining the effects of ACEss on threat learning. A consistent pattern emerged: individuals with a history of ACEss show diminished ability to discriminate between threat and safety signals, primarily due to reduced responding to the conditioned threat stimulus (CS+). This aligns with findings from Study 1 of the present dissertation, where childhood adversity was associated with reduced affective modulation of skin conductance responses (SCRs), again reflecting diminished discrimination between negative and neutral stimuli. Together, these findings point towards a converging picture in which exposure to childhood adversity points to reduced differentiation in the salience assigned to aversive cues. Notably, this pattern differs from what is typically seen in anxiety disorders, where impaired discrimination is usually driven by exaggerated responses to safety signals (CS-) rather than dampened responding to the CS+ (Duits et al., 2015; Cooper et al., 2018). Thus, adversity-related alterations in threat learning may reflect a mechanism distinct from - but potentially related to - pathways seen in clinical anxiety. One possibility raised in the literature is that adversity shapes the functioning of threat systems by reducing discrimination between neutral and aversive cues, whereas clinical anxiety is more often characterized by exaggerated and persistent threat responses or impaired extinction (e.g., Jovanovic et al., 2010; Duits et al., 2015; McLaughlin et al., 2016).

Across studies, ACEss were also robustly linked to impaired reward learning, as reflected in lower accuracy, fewer rewards earned, and slower acquisition of reward contingencies. These findings indicate reduced integration of reinforcement signals, consistent with blunted incentive salience rather than diminished hedonic capacity (Olney et al., 2018; Dillon et al., 2009). The overlap between these patterns and Study 1 is striking: whereas adversity-exposed participants in study 1 showed reduced SCR modulation in response to emotionally salient cues, the reviewed literature here suggests parallel deficits in updating behavior based on reward feedback. Both strands of evidence converge on the idea that adversity disrupts the adaptive tuning of motivational systems - whether in the context of avoiding threats or pursuing rewards. At the neural level, mixed findings were observed for reward anticipation (some studies showing blunted, others enhanced activity across reward-related regions), while consistent evidence pointed to hyperresponsivity to losses. This asymmetry underscores a potential shift in motivational balance following ACEss, whereby avoiding loss or punishment outweighs the drive to pursue rewards. Such shifts resonate with neuropathological models of anhedonia, where deficits lie in reinforcement-based learning and goal-directed action rather than in the capacity to experience pleasure (Pizzagalli, 2014).

One of the notable strengths of this literature review (Study 2) is that the pattern of blunted threat and reward learning emerged across diverse samples (children, adolescents, adults; healthy and clinical populations) and across heterogeneous paradigms, particularly in reward learning. The consistency across methodological diversity strengthens confidence that these learning alterations represent a reliable consequence of adversity exposure. At the same time, the meaning of this effect is less clear. Some authors have proposed that such alterations reflect latent vulnerability mechanisms that increase risk for later psychopathology (Gerin et al., 2017). Others have suggested that they may function as adaptive recalibrations to unpredictable or threatening environments (Litz Gray, 2002). Thus, while the robustness of the findings is evident, their interpretation—whether primarily maladaptive, adaptive, or context-dependent remains an important open question for future research.

A critical point of integration between Study 1 and Study 2 lies in the convergence of reduced discrimination. In Study 1, participants exposed to childhood adversity showed attenuated SCR differentiation between neutral and negative cues, while the systematic review in Study 2 identified blunted discrimination between CS+ and CS– across conditioning paradigms. Together, these findings suggest a broader difficulty in distinguishing relevant from irrelevant cues, whether in physiological responses to emotional stimuli (Study 1) or in associative learning tasks (Study 2).

At the same time, Study 1 indicated that the proximity of adversity may shape outcomes: recent adversity was linked to heightened sympathetic reactivity, whereas earlier experiences were linked to blunting. By contrast, the literature synthesized in Study 2 did not provide clear evidence that proximity systematically influenced learning outcomes. This discrepancy highlights the need to consider both the type of task (passive affective modulation vs. active conditioning) and the distinction between general reactivity and learning-specific processes.

Future work can address these questions more directly. More precisely, one approach could be to combine markers of general reactivity (e.g., baseline SCR or startle) with learning-based measures (e.g., reinforcement learning models, CS+/CS– discrimination) within the same participants. This would help determine whether blunted discrimination reflects a general dampening of arousal or a deficit specific to learning. Study 1 already provides initial evidence that the timing or proximity of adversity matters within a passive task. A next step could also be to examine whether such effects also emerge in paradigms that more explicitly engage learning processes, such as fear conditioning, reward learning. Longitudinal designs will be particularly important, as they can clarify whether blunted discrimination signals later vulnerability or instead stabilizes as an adaptive strategy under certain conditions.

5.1.3 Better Safe Than Sorry: Safety-Seeking Over Reward Pursuit in a Gamified VR Environment

The primary aim of the current study was to validate a newly developed VR task designed to elicit AA conflict behavior in dynamic and naturalistic settings. As predicted, participants displayed a robust "better safe than sorry" strategy. They spent significantly more time in the water context, which carried the lowest risk of aversive stimulation but also the lowest reward, while spending less time in the forest and desert contexts, which were associated with progressively higher threat probabilities. This pattern aligns with prior evidence from avoidance paradigms (Bach et al., 2014), where increasing threat led participants to preferentially remain in safer zones. Notably, participants' time allocation to the forest and desert was comparable, despite their differing threat–reward profiles. This suggests a potential "plateau effect," whereby avoidance stabilizes once a certain threshold of perceived threat is reached, regardless of additional rewards offered. Such a plateau echoes findings in both human and rodent models of avoidance (Klaassen et al., 2024), pointing toward a general mechanism by which individuals prioritize safety over maximizing reward.

Analysis of transition times further revealed avoidance tendencies. Participants exited the desert most quickly and frequently compared to the water and forest context. The desert's strong threat signal thus prompted rapid escape behavior and a direct return to safety. The low number of transitions from desert to forest suggests that intermediate contexts may lose relevance once individuals perceive danger as crossing a critical threshold. This risk-aversion pattern is consistent with translational models of avoidance such as the Open Field Test and Elevated Plus Maze, where both rodents and anxious humans rapidly retreat from threatening zones (Walz et al., 2016; Biedermann et al., 2017, 2022). Together, these findings highlight that leaving high-threat environments is not only frequent but also rapid, reflecting the prioritization of safety over exploration that characterizes avoidance behavior. While this pattern may serve adaptive functions in threatening contexts, in clinical settings such rapid withdrawal is linked to maladaptive avoidance and reduced flexibility. Crucially, however, the goal of this task was not only to demonstrate such avoidance patterns but also to establish that they can be reliably elicited and measured in an immersive VR setting, underscoring the paradigm's potential as a novel tool for studying AA processes.

Post-experimental self-reports further validated the behavioral data. Participants who emphasized reward-seeking tended to remain longer in the desert despite its higher punishment probability, whereas those focused on avoiding shocks preferred the water context. These associations confirm that participants' exploration patterns reflected underlying motivational priorities and converge with earlier studies linking subjective motivational ratings to avoidance behavior (Aupperle et al., 2011). Interestingly, avoidance ratings showed a small but significant negative correlation with time spent in the forest, while approach ratings were not predictive of behavior there. This suggests that for some individuals, even moderate-threat contexts elicited withdrawal tendencies, whereas approach motives primarily influenced behavior at the extremes of safety (water) or risk (desert).

A notable pattern emerged in the post-exploration phase: participants increased their time in the forest, while the desert remained largely avoided. This suggests that once immediate task demands were removed, participants were willing to re-engage with the moderately threatening forest, but not with the highly aversive desert. Prior research indicates that habituation is more likely under conditions of moderate and predictable threat (Alvarez et al., 2011), whereas strong or uncontrollable threats are resistant to habituation and can even lead to sensitization (Blumstein, 2016). The forest thus appears to have represented a "comfortable middle ground," balancing tolerable risk with the opportunity for reward. This flexibility illustrates the potential utility of immersive VR tasks for translational research: while not designed as a therapeutic tool, the present paradigm suggests how gamified exposure to moderate-threat environments might facilitate adaptive re-approach behavior in clinical contexts.

Physiological results revealed a complex interplay between context, exploration phase, and arousal. During pre-exploration, skin conductance levels (SCL) were highest in the forest, consistent with anticipatory arousal in response to ambiguity (Gray McNaughton, 2000; Aupperle Paulus, 2010). In contrast, the water and desert contexts may have been easier to categorize, eliciting lower anticipatory responses. Across all contexts, however, SCL rose significantly from pre- to post-xploration, indicating that active navigation and task engagement served as a global amplifier of sympathetic activation.

This pattern diverges from work showing that natural environments reduce arousal through passive exposure (Anderson et al., 2017; Knaust et al., 2022). The difference highlights the role of active engagement: immersive, goal-driven VR scenarios reliably elicit elevated EDA compared to passive viewing (Zimmer et al., 2021; Marín-Morales et al., 2020).

Contrary to expectations, BIS/BAS trait scores did not predict exploration patterns. Instead, situational motivational ratings ("tried to get the highest score," "tried to avoid shocks") explained individual differences more effectively. This suggests that under conditions of high threat, immediate context-specific motivations dominate behavior, whereas dispositional traits such as BIS/BAS may fail to capture meaningful variance. These findings highlight the importance of assessing real-time motivational states for understanding decision-making under risk, rather than relying solely on trait-level questionnaires.

In sum, this study validated a novel VR paradigm for investigating AA conflict in naturalistic settings. Participants consistently prioritized safety over reward, showed rapid escape dynamics under high threat, and flexibly re-engaged with moderately threatening environments after task completion. Subjective motivational ratings mapped onto behavior, while trait-level BIS/BAS scores did not, underscoring the primacy of situational over dispositional predictors in conflict decision-making. Taken together, these findings highlight the potential of immersive, gamified VR tasks not only as ecologically valid tools for studying AA conflict, but also as promising foundations for translational research on maladaptive avoidance, motivational trade-offs under threat, and exposure-based interventions.

Regarding the analysis of early adversity exposure and its association with behavioral data, the most robust effect emerged for transition latencies. Both groups adjusted their speed depending on the starting and target contexts, but in different ways. CM− participants moved faster from water to desert than from water to forest, suggesting that the desert's high-reward potential outweighed its threat value and motivated a quicker approach. By contrast, CM+ participants did not differentiate between these two transitions, approaching desert and forest with comparable latencies. This pattern points less to a failure of discrimination and more to heightened caution or reduced motivational drive toward high-risk, high-reward options. Such behavior aligns with prior evidence that exposure to early adversity biases avoidance-oriented responding, as seen in altered avoidance learning in adults with childhood trauma (Herzog et al., 2021), and hampers conflict regulation when threat and goal signals compete, reflected in disrupted emotional-conflict control in adversity-exposed youth ((Marusak et al., 2015). Similar mechanisms are also discussed in broader models of anxiety and motivational dysfunction (Aupperle Paulus, 2010;describing impaired AA conflict resolution; and (Kangas et al., 2022), outlining shifts in motivational balance toward loss avoidance at the expense of reward pursuit).

Exploration times did not differ overall between CM− and CM+ participants, but the direction of change from pre- to post-exploration diverged. CM− participants increased their time in the desert, suggesting a normative shift toward exploiting the high-reward, high-threat context once contingencies were clear, consistent with work showing that human decision-making involves a balance between exploratory sampling and exploitative reward maximization (Daw et al., 2006). CM+ participants, in contrast, reduced their time in the water context - a safe but low-reward environment - and increased their time in the forest. This pattern suggests a more cautious strategy: rather than fully committing to the desert, as CM− participants did, CM+ individuals shifted engagement toward the forest, which combines moderate threat and moderate reward. Both groups thus appeared to increase engagement with ambiguity after learning contingencies, but they differed in their tolerance for risk - CM− participants accepting the high threat of the desert, CM+ participants preferring the compromise of the forest.

These behavioral shifts resonate with broader evidence that ACEss alter the systems underlying threat and reward learning. As summarized in Study 2 (see Chapter 3), adversity is linked to blunted discrimination between threat and safety cues and to impaired reward learning, suggesting reduced flexibility in how reinforcement values are updated (Dillon et al., 2009; Olney et al., 2018). This aligns with Study 1 (see Chapter 2), where adversity-exposed participants showed blunted physiological discrimination between negative and neutral stimuli, suggesting not a complete absence of discrimination but reduced precision in tuning responses to contextual salience. In the current VR task, the CM+ group's shift from water to forest may similarly reflect a cautious recalibration of motivational balance, favoring moderate levels of stimulation while avoiding both very safe/low-reward and high-risk/high-reward contexts. By contrast, the CM− group's increased desert engagement reflects normative reward-driven exploitation. Together, these patterns align with models proposing that ACEss bias motivational trade-offs toward heightened avoidance of loss and reduced pursuit of potential rewards (Pizzagalli, 2014; Smith et al., 2025). Although the current results did not yield a robust three-way interaction, they converge with prior behavioral and neural findings suggesting that early adversity alters how individuals balance risk, reward, and safety in adaptive decision-making.

5.1.4 Limitations

While the three studies presented in this thesis offer important insights into the relationship between early childhood adversity, recent adversity and threat–reward processing, several limitations should be considered in order to contextualize the findings. Discussing these caveats is essential not only for interpreting the results of the individual studies, but also for outlining directions for future work. Below, I address study-specific limitations of the first two experiments before moving to broader considerations.

Study 1.

Study 1's generalizability to clinical samples is constrained since individuals with psychiatric diagnoses were excluded. Consequently, individuals who have faced adversity, particularly early adversity, yet remained healthy might be considered "supercontrols", limiting the generalizability of the results. Indeed, (McTeague Lang, 2012) and Lang (2012) observed exaggerated startle reactivity exclusively in patients suffering from PTSD, not in control participants, regardless of trauma exposure. Furthermore, (Stout et al., 2021) demonstrated a robust association between blunted startle reactivity and exposure to childhood adversity when controlling for PTSD symptoms, depression, and anxiety. Similarly, (Medina et al., 2001) reported blunted startle responses in patients qualifying for a PTSD diagnosis compared to those who did not, but found no differences when considering exposure alone. Consequently, longitudinal and prospective research is warranted to elucidate the (pathological vs. non-pathological) trajectories following adversity exposure, given the heterogeneity of the literature and the sample populations (i.e., healthy, at risk, patients) from which results are derived. This heterogeneity precludes definitive conclusions regarding risk and resilience in the extant literature. Additionally, this study's retrospective assessment of adversity introduces potential memory biases, a subject of ongoing debate in the literature (Baldwin et al., 2019). Evidence from (Danese Widom, 2020) indicates that even severe cases of childhood maltreatment confirmed through court records were not associated with elevated psychopathology unless individuals also subjectively reported these experiences, whereas subjective reports alone consistently predicted greater risk. Conversely, the risk of psychopathology linked to subjective reports of childhood adversity remains high, irrespective of consistency with objective measures (Danese Widom, 2020). Although recall bias has been suggested to account for less than 1% of report variance (Fergusson et al., 2011), it is crucial to acknowledge that prospective and retrospective measures of childhood adversity identify different groups of individuals (Baldwin et al., 2019).

Study 2.

Although the aim was to examine a broad range of tasks involving both threat and reward, the available literature did not allow for equal representation across paradigms. The analysis included disproportionately more studies on classical fear and reward conditioning compared to paradigms such as the NPU (no shock, predictable shock, unpredictable shock) or shock-threat tasks. As a result, the conclusions are weighted more heavily toward conditioning studies, which may exert disproportionate influence on the overall interpretation. Moreover, only a small number of studies involved clinical populations, and very few focused on adolescents (n = 4). This means that the synthesis primarily reflects findings from non-clinical adult samples, limiting the generalizability of conclusions to those most affected by stress-related disorders or to developmental periods of heightened plasticity such as adolescence (Sisk Gee, 2022).

Study 3.

The third study also has several important limitations. One constraint is that the task design tested only parallel pairings of threat and reward levels (e.g., low threat–low reward; high threat–high reward), without including mixed combinations such as high reward coupled with low threat. This restricted design leaves open the possibility that different motivational trade-offs might have emerged under alternative conditions, particularly in scenarios that combine high incentives with minimal risk. Another limitation concerns the virtual environments themselves. While the water, forest, and desert contexts were conceptually created to be clearly distinguishable, we did not assess participants' subjective associations with these environments. For example, some individuals may have brought negative personal associations to the forest environment, or differed in their subjective liking of the tokens used as rewards. Such idiosyncratic responses could have influenced behavior but were not systematically measured. Moreover, decisions about environmental details, textures, and contextual elements are known to shape presence in virtual environments (Slater, 2009), but they also introduce the possibility of participants becoming engaged with aspects of the environment that were not central to the research question (Neo, 2021). A further methodological limitation relates to navigation. Although we measured behavior through participants' virtual movement across contexts, this movement was achieved exclusively through joystick control rather than through natural bodily movement (e.g., walking or head-turning). This may reduce the ecological validity of the findings, since joystick-based navigation does not fully capture the embodied responses people typically show to threat or reward cues. Finally, the physiological measures in this study were constrained by technical issues. Electrodermal activity recordings suffered substantial data loss, primarily due to movement artifacts caused by the non-dominant hand, even though this hand was not required for active control. As a result, the reliability of the EDA findings is limited, and conclusions drawn from these measures should be interpreted cautiously.

5.2 Synthesis of Findings and Broader Implications

Adverse childhood experiences (ACEss) are among the most powerful predictors of long-term mental and physical health, shaping how individuals process emotions, learn from their environment, and navigate risks and rewards across the lifespan (Felitti et al., 1998; McLaughlin et al., 2014; Teicher Samson, 2016; Ruge et al., 2024). Existing research has provided compelling evidence that ACEss recalibrate physiological and cognitive systems, leaving traces in defensive reactivity, associative learning, and motivational patterns. At the same time, much of this work has been carried out in highly controlled laboratory settings that, while invaluable for isolating mechanisms, capture only fragments of the complex situations people face in everyday life. This creates a central challenge for the field: how can robust, validated findings on adversity's association be linked more directly to the dynamic, context-dependent behaviors that unfold outside the lab? Far from undermining prior evidence, addressing this challenge offers the opportunity to integrate well-established knowledge with new methods that enhance authenticity in experimental settings (see Section 1.3.1). Immersive paradigms may serve as a bridge, allowing researchers to retain experimental control while capturing the richness of real-world emotional and motivational trade-offs.

This dissertation set out to investigate how ACEss shape physiological processing, threat and reward learning as well as motivated behavior through approach and avoidance behaviour. At the same time, it examined how immersive, gamified paradigms can move beyond traditional laboratory settings, providing more authentic insights into how individuals balance risk, safety, and reward in dynamic environments. Taken together, the studies reflect a broader aim: to shed light to the mechanisms through which exposure to early childhood adversity becomes "embedded" in affective and motivational systems, while also testing how these mechanisms manifest when individuals are placed in situations that more closely approximate everyday challenges. By combining psychophysiological measures, systematic evidence synthesis, and immersive virtual reality, the work connects multiple levels of analysis ranging from autonomic reactivity to the complexity of real-time AA challenges. This layered approach suggests that ACEss are linked not only to vulnerabilities (e.g. difficulties in emotional discrimination, impaired learning, or heightened avoidance tendencies) but also to adaptive recalibrations and cautious strategies that may emerge in response (e.g. shifting away from extreme high-risk choices toward more moderate, manageable options). Such mid-range strategies are consistent with evidence that under uncertainty people tend to explore more cautiously rather than committing to extremes (Reitich-Stolero et al., 2025). At the same time, adversity-related adaptations are not restricted to blunting or caution. Recent work shows that maltreated adolescents can even display enhanced behavioral flexibility in volatile reward-learning contexts, adapting more quickly after contingency shifts (Waltmann et al., 2025). A similar idea is reflected in the VR findings from Study 3, where adversity-exposed participants did not withdraw altogether but adopted compromise strategies when faced with uncertain trade-offs.

These patterns suggest that adversity can sometimes promote adaptation when environments are unstable or rapidly changing. In contrast, the paradigms used in Studies 1 and 2 involved relatively predictable cue–outcome pairings, and here adversity was linked to blunted differentiation and impaired learning. Together, this comparison points to a broader possibility: adversity-linked adaptations may be beneficial in volatile contexts but come at a cost in structured, predictable ones.

The three studies presented in this dissertation contribute complementary perspectives on these processes. Study 1, which relied on a predictable paradigm (passive picture viewing with clearly defined emotional categories), demonstrated that childhood maltreatment was linked to blunted differentiation between neutral and negative stimuli in skin conductance responses, while more recent adverse experiences amplified sympathetic arousal (see Chapter 5.1.1). This divergence underscores that adversity's association is not monolithic but varies with its temporal proximity to adversity exposure, a finding consistent with models proposing that early adversity recalibrates affective systems toward dampened modulation, whereas recent stress sensitizes physiological reactivity (McLaughlin et al., 2014; Teicher Samson, 2016; (Scharfenort et al., 2016)). Study 2 extended this picture by synthesizing evidence across fear- and reward-learning paradigms. The review highlighted robust deficits in discrimination between threat and safety cues and impaired reward learning in individuals with ACEs histories, reinforcing the idea that adversity is associated with differences in how reinforcement signals are integrated (see Chapter 5.1.2). From a clinical perspective, such alterations may represent modifiable plasticity processes at the core of interventions like cognitive behavioral therapy, though most existing studies rely on group-level inferences (Ruge et al., 2024). A critical next step is therefore to develop approaches that can track such learning processes at the individual level. Immersive paradigms such as the VR task in Study 3 offer one promising route, as they combine experimental control with authentic, dynamic contexts and generate rich trial-by-trial data that capture individual-level adaptation—a prerequisite for clinical translation—while allowing the investigation of how these processes manifest in real-time AA conflict.

Participants navigated trade-offs between risk and reward within an immersive VR environment, capturing the dynamic conflicts between approaching incentives and avoiding threats that characterize everyday decision-making. While the overall sample prioritized safety, consistent with "better safe than sorry" strategies, childhood adversity-exposed participants distinguished themselves by adopting more cautious engagement. Rather than exploiting the high-risk/high-reward desert context, they shifted exploration toward the forest, which carried intermediate threat and reward.This pattern suggests that ACEss may bias motivational strategies in conflict situations toward cautious compromise rather than reward maximization. Broader research also shows, however, that individuals with ACEs histories are at increased risk for behaviors such as substance use and delinquency (Felitti et al., 1998; Widom, 1989). These findings may reflect different expressions of adaptation: in structured experimental contexts like the VR task, adversity-exposed individuals may lean toward caution, whereas in everyday life, other pressures or coping motives can lead to risk-taking. Thus, the cautious approach observed here should not necessarily be interpreted as maladaptive withdrawal, as in some contexts it may function as a resilience strategy in uncertain or volatile environments.

This interpretation resonates with broader resilience research, This interpretation resonates with resilience research, which investigates the conditions and factors that enable individuals to adapt positively despite adversity. Yet, the variability in behavioral strategies observed here (i.e. some individuals still pursuing high-risk rewards) highlights that adversity may not determine outcomes uniformly. Instead, protective influences may shape whether cautious recalibration manifests as adaptive flexibility or maladaptive constraint. For instance, although this was not the primary focus of this thesis, benevolent childhood experiences (BCEs; e.g. supportive relationships or school engagement) have been identified as one such factor, namely, they can buffer against the psychological costs of exposure to early adversity (Hou et al., 2022; Merrick et al., 2019), and that resilience mediates the link between positive early experiences and later well-being across cultures (Sever et al., 2024). Neural findings further suggest that adversity may not lead to a single outcome but could influence emotional and motivational systems in different ways depending on context. For instance, frontolimbic connectivity has recently been shown to mediate the link between threat exposure and later psychopathology (Antonacci et al., 2025). Rather than contradicting the blunting perspective, such findings suggest that adversity may lead to different outcomes depending on context: it can be linked to dampened responses, such as reduced SCR differentiation between neutral and negative cues (Study 1); to heightened sensitivity, as observed with recent adversity amplifying sympathetic arousal; or to more flexible adaptations, for example faster adjustment in volatile reward-learning tasks (Waltmann et al., 2025). In sum, to synthesize the contributions of this dissertation, the three studies together provide a layered picture of how adversity becomes embedded in affective and motivational systems. Study 1, using a predictable passive viewing paradigm, showed that childhood maltreatment was linked to blunted differentiation between neutral and negative stimuli, whereas recent adversity amplified sympathetic arousal. Study 2, synthesizing evidence across fear- and reward-learning paradigms, revealed robust impairments in discrimination between safety and danger cues and reduced reward learning, suggesting that physiological differences extend into altered associative learning. Study 3 extended this to motivated behavior in an immersive VR task: adversity-exposed participants shifted away from high-risk/high-reward options toward intermediate, compromise-oriented strategies. Taken together, these findings suggest that adversity is associated with reduced precision in distinguishing between threat, safety, and reward signals, with consequences observable across physiological reactivity, associative learning, and real-time decision-making.

Crucially, Study 3 also highlighted a methodological advance. Traditional laboratory paradigms often capture only fragments of emotional processing (i.e. isolated reflexes, passive picture viewing, or tightly constrained conditioning tasks). By contrast, the immersive, gamified VR paradigm placed participants in a dynamic environment where decisions carried immediate consequences for safety and reward. This approach preserved experimental control while enhancing authenticity,

echoing calls in real-world neuroscience to bridge the gap between simplified laboratory tasks and the complexity of naturalistic environments (Matusz et al., 2019). Future progress will likely depend on extending beyond simplified laboratory tasks to embrace ecologically valid paradigms (like immersive VR) that approximate the richness of cognition and behavior in everyday contexts (Parsons, 2024). In line with these broader methodological discussions, Study 3 showed that the incorporation of game-like features fostered motivation and autonomy, addressing a challenge in human experiments: how to elicit goal-directed behavior that mirrors real-world engagement.
Looking forward, the implications extend in several directions. First, the findings call for a more nuanced view of associations with adversity, moving beyond simple models of hyper- or hypoeactivity. For example, Study 1 showed that adversity was linked to blunted physiological discrimination, while Study 3 revealed more cautious behavioral strategies in AA conflict. Together, these results suggest that future research should explicitly test when such cautious strategies provide adaptive value (e.g., under volatile conditions) versus when they signal impaired flexibility (e.g., in predictable, low-threat environments). Second, they underscore the need to bridge levels of analysis: future studies could combine psychophysiological markers with computational models of learning (e.g., reinforcement learning models to estimate how adversity affects updating from positive vs. negative outcomes, or drift–diffusion models to separate whether slower responses reflect reduced salience of cues or more cautious decision thresholds; Vermeent et al., 2025; Vermeent et al., 2025). Third, the present findings point to variability within adversity-exposed groups. While our analyses focused on group-level differences—such as blunted SCR differentiation (Study 1) and cautious AA strategies (Study 3)—not all individuals with adversity histories followed the same patterns. This raises the question of which factors might explain such variability. Although our work did not assess these moderators directly, prior research has highlighted candidates such as cognitive control and emotion regulation abilities (Compas et al., 2017) or protective experiences like benevolent childhood experiences (Hou et al., 2022; Merrick et al., 2019; Sever et al., 2024). Beyond categorical exposure, the subjective experience of adversity (and the alignment between physiological signals and felt emotion) may be crucial. Recent evidence shows that individuals can report similar affective states while displaying divergent physiological profiles, a dissociation particularly evident in affective disorders (Cuve et al., 2023). Relatedly, our own work demonstrates that combining subjective ratings with physiological indices can reveal such mismatches at the individual level (Koppold et al., 2024), underscoring the value of integrative approaches for identifying when adversity-linked patterns reflect vulnerability versus resilience. Beyond these, the way adversity itself is assessed is crucial: evidence indicates that commonly used questionnaires differ markedly in the types of experiences they capture (Koppold et al., 2024). This measurement heterogeneity means that findings like blunted discrimination or cautious engagement may partly depend on whether threat, deprivation, or unpredictability exposures are emphasized. Future work therefore needs to carefully align measurement choices with theoretical models, to clarify when adversity-linked patterns reflect vulnerability and when they may instead indicate adaptive recalibration. Importantly, there is also a strong methodological call. Understanding emotional

processing and motivated behavior as they unfold in daily life requires moving beyond tightly controlled lab tasks toward more reproducible, collaborative, and scalable approaches. Immersive VR combined with gamification offers such a platform, not only for studying emotional dynamics in ecologically valid contexts, but also for translation and intervention, serving as both a precise assessment tool and a training ground for adaptive strategies (e.g. exposure-based or resilience-uilding programs). To realize this potential, the field must embrace shared protocols, open-source tools, and coordinated data collection across labs, ensuring that VR paradigms are replicable and adaptable (experiments as code approaches; Aguilar et al., 2024). This also necessitates the inclusion of diverse, longitudinal samples, which are essential for capturing real-world heterogeneity and resilience trajectories - something often lacking in traditional cross-sectional designs. From a technical standpoint, advances like 3D Gaussian Splatting (Kerbl et al., 2023) now enable high-idelity, real-time rendering of immersive environments, raising the bar for ecological realism without sacrificing performance (e.g., realistic facial immersion; (Barthel et al., 2023, 2024). Furthermore, current studies (also Study 1 in this thesis) relied on static images with post-stimulus ratings of arousal and valence, new tools now make it possible to capture affective dynamics more directly. For instance, continuous affect tracking during 360° immersive stimuli (e.g., Fourcade et al., 2024) allows moment-to-moment measurement of valence and arousal, offering richer opportunities to link subjective states with physiology and behavior. Although such methods still require careful standardization and validation, much like traditional paradigms, they illustrate a promising direction for advancing the field.

Chapter 6

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Chapter 7

Acknowledgement

The memory of walking past the institute door and into the office for the first time is still vivid, even though six years have passed. Some memories don't age - time doesn't wear them down the way it changes your body and your sense of self. In that memory lives a small sentence: *"Enjoy the journey."* It has followed me through these six years. I've returned to it many times, in different moments and phases. The answer wasn't always simple - and often it wasn't *"yes."* But as I write these words now, I'm glad I chose this path. I've grown as a scientist and, even more, as a person, and the joyful moments are the ones that come first to mind. That said, acknowledgements are usually for gratitude and thanks. Still, I feel the need to say a few words about the negative aspects - even if it sounds a bit cynic. Naming them as they are, however idiosyncratic my view may be, is the only way to change them. So:

One part of my "growing up" was realizing how much I used to romanticize the pursuit of science - or perhaps was even disillusioned about it - by overlooking the many difficulties that make up the whole picture. Not anymore. Today, as I write these words, I think of people close to me who have faced, or are still facing, academic abuse, racism, manipulation, and unhealthy dependencies on their superiors, often forced into silence: *"I can't speak now, I'll finish my PhD first."* On the one hand, it is deeply disappointing to see how hard it is to change this. It is not only about individuals but about a system that silently supports such circumstances - looking away, keeping up the illusion of a "happy academic family," while at the same time glorifying a distorted idea of *excellence*. Instead of standing for solid and meaningful research, excellence is often equated with "faster, more, and shinier" - rewarding volume, speed, and efficiency over care, fairness, and soundness. This pressure creates environments where careful work and fair treatment are easily sacrificed, as long as the results appear "excellent." However, this does not mean that everything is cynical. There are also hopeful signs, and I do still believe in change. I see more peer-support groups forming, especially among younger generations, and the topic is becoming less stigmatized and more openly discussed. This does not solve the problem, but it is at least a hopeful beginning.

With this said, I want to move on to the “thank you” part, since this journey would not have been the same without the people who shaped it. Starting with my academic community, I want to thank you, Tina. Within the circumstances I described above - and since it should never be taken for granted - I am deeply grateful for the conditions you created for me as a supervisor and mentor in these first academic steps. You gave me the space, time, and resources to explore my own ideas, to be creative, and the freedom to implement them - and, importantly, to make my own mistakes. Most of all, I felt truly supported and protected in my most vulnerable moments. Usually a supervisor speaks from the perspective of watching their students grow. But there is also the other side: a student sees their supervisor grow as well. Watching you, Tina, continue to grow while keeping your values constant is rare, inspiring, and motivating. It makes me optimistic about the academic future. Thank you for that.

I am also grateful for all the encounters I had throughout this academic journey. I would like to thank the whole lab, especially the people I got to know better - Alina, Mana, Maren, Maria, and Julia - as well as former members who left the group shortly after I started but still inspired me, Manu and Rachel. I am also very thankful to all our student assistants who supported me along the way - especially with the challenge of running my complex VR task. Many thanks for that.

After our lab’s return from the COVID-19 lockdowns, a reorganization of the rooms brought me to the wonderful room 328 at iSN, together with Maren, Alina, and Tatia. Thank you for being open to listening and talking about everything - from silly (and often bad) jokes to serious problems - and for supporting me throughout this time. Thank you for allowing me to be myself in full authenticity at our workplace, and for giving me another reason to look forward to coming in every day.

Madeleine and Björn, you were among my very first encounters at iSN. Thank you for the creative spark you brought into my life, for the gaming nights, the imaginative talks, and the countless moments of laughter.

Finally, a big thanks to Carolina: you always kept your door open and were ready to help with the many administrative issues that came up. Even in my lowest moments, I felt supported - not only administratively, but emotionally as well.

On a personal level, these few lines can’t capture how grateful I am to have you in my life, bringing out the best in me: Totti, Hanna, Felix, Lina, Bente, Rainer, Ida, Fritz, Gosia, Kayson, Fatemeh, Rebecca, Fabrizio, Rabea, Kaan, and all the Wilhelmsburg friends - especially Bente, Rainer, Fritz, Ida, Steffi and Björn, Gosia, Dragan, Simos, Fedra, Myrto, Petros (Freestone) and Giorgos (Zoom).

Matina, thank you for being so supportive and for creating an environment of joy, laughter, and safety during these past few months.

Fred, Isa, Jaro, and Emma - thank you for being, quite literally, a second family to me.

A special thanks to my current Mind-Body-Emotion group, who were such a big part of my final steps and endlessly supportive - my favorite 3A’s: Aleksandra, Antonin, and Anthony.

And Micha - thank you for being such an inspiring and motivating mentor, teaching me not only to critique but also to rethink academia from a modern perspective.

The very first day I walked into the iSN, exploring the office and meeting the second PhD student I'd be working with on the FearProfiles project, I could never have guessed how much that moment would come to mean to me. Alina, you've shown me what real friendship is - so much more than I ever thought possible. You've been there for me in my lowest moments and in my happiest ones. You've seen both sides of me - the messy and the bright - and never turned away. Instead, you gave me acceptance, strength, and kindness that changed how I see myself and the people I hold close. You keep inspiring me, reminding me that things I once thought impossible can be done. Because of you, I've dared to believe in myself and to try things I might have given up on. Your openness and authenticity make me want to follow my own path and be the person I truly want to be. Some friendships just happen, but a few feel like they'll last forever - built on trust and care so deep they become part of who you are. Ours is one of those. And for that, I'm endlessly grateful.

Thank you, Giorgo (Classmate), for truly being like a brother to me - for being one of the most steady, grounding parts of my life. Even though I've spent almost half my life away from Crete, you've kept the island feeling like "home," always with an open hug and a safe place for me to return to. Growing up alongside you remains one of the most valuable parts of my life. I'm deeply grateful for you always being there.

Lazare - aka Rcane. I have tried to find the right words, but words never feel enough to express how fortunate I am to have experienced a part of your endless creativity, wisdom, and your way of seeing life and what truly matters. You are the "shaman," always one step ahead, showing me the way. Your voice always whispers in my mind - through your Socratic questioning, provoking me, pushing my thoughts further. You are a living spirit that continues to walk beside me in every step. Together with the "Transmuting Bandit," the "Lizard Man", the "Diver", and all the other wonderful creatures of your artwork, where so much of you lives on, you remind me to stay free in thought and to face challenges with courage, merit, and bravery.

Next, I would like to thank my mom, dad, and sister. This feels like a nice moment to echo - in paraphrased form - a line from this thesis: "Childhood experiences shape who we are today, our decisions, and the way we respond to navigate through daily life". I would not be who I am without you. You have taught me what it means to love unconditionally, giving me more than a child could ever ask for during the years that shaped me. I didn't always understand the way you expressed your love, but I could always feel it - and I learned to give it back. To my mom, Jenny: thank you not only for being a mother, but also a true friend. Thank you for your open mind, for listening to me no matter the occasion, and above all, for the emotional sacrifices you made so we could find our own paths. To my dad: thank you for inspiring in me a love of knowledge, curiosity, and the search for answers. You taught me to face challenges with patience, clarity, and fairness - and thank you for your endless patience when trying to teach me physics and chemistry, even though I didn't make it easy. And to my sister, Meleni: you are the most "sister" a sister could be. Thank you for your endless care and for protecting me in the moments I struggled to do so myself. You have shown me what it means to be brave in the face of the hardest challenges, to truly care for

each other, to be respectful, and to bring light when my path grew dark. I cannot think of the word family without you.

Acknowledgment of AI Assistance

This dissertation has made use of generative Artificial Intelligence (AI) technologies for technical and linguistic support. Specifically, AI tools were employed for code assistance (including partial support with visualization), grammatical and orthographical correction, improvements in linguistic clarity, support with structuring, and ensuring overall coherence and consistency of the text. The tools used were ChatGPT (Model 4.1) provided by the GWDG (Gesellschaft für wissenschaftliche Datenverarbeitung mbH Göttingen) and Perplexity. AI was not used for generating scientific ideas, suggesting or selecting literature, or contributing to the research content of this dissertation.

Acronyms

AA Approach-Avoidance. 18, 57–59, 78, 83–85, 89, 90, 92, 122

ACC anterior cingulate cortex. 122

ACEs Adverse Childhood Experiences. 5–7, 18, 43–45, 47, 49–54, 77, 78, 81, 82, 86, 89, 90, 122

ASM Affective Startle Modulation. 23, 122

BAS Behavioral Activation System. 58, 59, 62, 66, 72, 84, 85, 122

BD BAS-Drive. 59, 62, 66, 72, 122

BDI Beck's Depression Inventory. 27, 28, 122

BIS Behavioral Inhibition System. 59, 62, 66, 72, 84, 85, 122

BOLD blood-oxygen-level dependent. 45, 122

CM childhood maltreatment. 65, 72–74, 122

CTQ Childhood Trauma Questionnaire. 24–27, 30, 38–40, 59, 60, 78, 81, 122

dACC dorsal anterior cingulate cortex. 52, 122

ECG Electrocardiography. 9, 122

EDA Electrodermal activity. 84, 88, 122

ELA Early Life Adversity. 122

EM Emotional Regulation. 122

EMG Electromyography. 9, 23–28, 32, 33, 37, 38, 78–80, 122

EMM estimated marginal mean. 67, 68, 73, 122

EPM Elevated Plus Maze. 122

fMRI functional magnetic resonance imaging. 122

FPS Fear-Potentiated Startle. 122

FUN BAS-Fun Seeking. 59, 62, 72, 122

GAD Generalized Anxiety Disorder. 122

KERF German Maltreatment and Abuse Chronology of Exposure. 25–27, 38–40, 78, 81, 122

LTE List of Threatening Experiences. 26, 30, 122

MACE Maltreatment and Abuse Chronology of Exposure. 26, 78, 81, 122

MID Monetary Incentive Delay. 122

OFT Open Field Test. 122

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses. 122

RA Recent Adversity. 122

RR BAS-Reward Responsiveness. 59, 62, 66, 72, 122

RST reinforcement sensitivity theory. 58, 122

SCL Skin Conductance Level. 69, 70, 122

SCR Skin Conductance Responses. 9, 23–25, 27, 28, 32, 33, 37, 78–83, 91, 92, 122

SDT Self-Determination Theory. 122

SSDR Species Specific Defensive Responses. 10, 122

STAI State-Trait Anxiety Inventory. 26, 27, 122

vmPFC ventromedial prefrontal cortex. 52, 122

VR Virtual Reality. 13, 14, 57, 58, 61–64, 83–86, 89–93, 122

Erklärung des Eigenanteils

In dieser Dissertation wurden drei Studien präsentiert. Für jede dieser Studien wird im Folgenden mein individueller Beitrag aufgeführt:

Studie 1:
Mein Eigenanteil umfasste: *Konzeption; Datenaufbereitung; formale Analyse; Methodik; Software; Validierung; Visualisierung; Verfassen des ursprünglichen Manuskripts; Verfassen – Überarbeitung und Redaktion*.

Studie 2:
Mein Eigenanteil umfasste: *Datenaufbereitung; Datenerhebung; Verfassen des ursprünglichen Manuskripts; Verfassen – Überarbeitung und Redaktion*.

Studie 3:
Diese Studie ist mit Stand September 2025 noch nicht publiziert, peer-reviewt oder eingereicht. Mein Eigenanteil umfasste: *Konzeption; Datenaufbereitung; formale Analyse; Methodik; Software; Validierung; Visualisierung; Verfassen des ursprünglichen Manuskripts; Verfassen – Überarbeitung und Redaktion*.

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